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Volume 10 · Issue 20 | October (II) 2020

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Special Issue "Advanced Technologies in Wood Science"

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A special issue of *Applied Sciences* (ISSN 2076-3417). This special issue belongs to the section "**Environmental Sciences**".

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Laboratory of Wood Science - Chemistry & Technology, Department of Forestry & Natural Environment, School of Geotechnical Sciences, International Hellenic University, Thermi, Greece
Interests: wood; wood composites; lignocellulosic materials; chemical and thermal modification technologies; nanotechnology and nanomaterilas; adhesives
Special Issues and Collections in MDPI journals

Special Issue Information

Dear Colleagues,

Wood, a versatile material, has been used for centuries for many reasons due to its fibrous nature. It varies in color and density and is considered a primary raw material in buildings due to its high strength in combination with its low weight and some durability. It is, therefore, a raw material that can be used in indoor applications and, if treated efficiently, in outdoor application as well. However, wood has two main disadvantages which restrict its wider use, namely a susceptibility to biodegradability by microorganisms and a dimensional instability when subjected to a varied moisture content. Most wood species deteriorate rapidly under biological factors; the most important biological decay is caused by fungi. On the other hand, when wood is subjected to a fluctuating moisture, dimensional and conformational instability occur. These drawbacks are mainly due to the cell wall main polymers and, in particular, due to their high abundance of hydroxyl groups. Wood may be modified chemically or thermally, so that selected properties are enhanced in a more or less permanent fashion. Another option to improve these properties is to exploit the solutions that nanotechnology can offer. The small size nanoparticles of nanotechnology compounds can deeply penetrate into the wood, effectively alter its surface chemistry, and result in a high protection against moisture and decay. In addition, the use of lignocellulosic materials for the production of advanced wood composites is an innovative avenue for research. This Special Issue, Advanced Technologies in Wood Science, seeks high-quality works and topics (not only those) focusing on the latest approaches to the protection of wood and wood composites with chemical or thermal modification technologies, the application of nanomaterials to wood science and the development of new techniques and technologies for production of lignocellulosic materials with enhanced properties and performance.

Assoc. Prof. Antonios Papadopoulos
Guest Editor

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Wollastonite to Improve Fire Properties in Medium-Density Fiberboard Made from Wood and Chicken Feather Fibers

by Hamid R. Taghiyari, Jeffrey J. Morrell and Antonios N. Papadopoulos

Appl. Sci. **2021**, *11*(7), 3070; https://doi.org/10.3390/app11073070 - 30 Mar 2021

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Abstract Poultry is a crucial global protein source.However, processing creates sizable quantities of feathers as a by-product. Identifying suitable uses for these feathers poses a major challenge. One possible use would be as an extender in medium density fiberboards (MDF). At the same time, [...] Read more.

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Possibilities of Decreasing Hygroscopicity of Resonance Wood Used in Piano Soundboards Using Thermal Treatment

by Petr Zatloukal, Pavlína Suchomelová, Jakub Dömény, Tadeáš Doskočil, Ginevra Manzo and Jan Tippner

Appl. Sci. **2021**, *11*(2), 475; https://doi.org/10.3390/app11020475 - 06 Jan 2021

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Abstract This article presents the possibilities of decreasing moisture sorption properties via thermal modification of Norway spruce wood in musical instruments. The 202 resonance wood specimens that were used to produce piano soundboards have been conditioned and divided into three density groups. The first [...] Read more.

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Evaluation of Color Change and Biodeterioration Resistance of Gewang (*Corypha utan* Lamk.) Wood

by Dodi Nandika, Wayan Darmawan, Lina Karlinasari, Yusuf Sudo Hadi, Imam Busyra Abdillah and Salim Hiziroglu

Appl. Sci. **2020**, *10*(21), 7501; https://doi.org/10.3390/app10217501 - 26 Oct 2020

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Abstract Gewang (*Corypha utan* Lamk.) is one of the endemic palm species which has been used as a building material for many years in Indonesia. The objective of this study was to enhance the overall resistance of gewang wood to biological deterioration by [...] Read more.

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

by Muhtar

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Abstract Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete [...] Read more.

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Termite Resistance of Furfuryl Alcohol and Imidacloprid Treated Fast-Growing Tropical Wood Species as Function of Field Test

by Yusuf Sudo Hadi, Elis Nina Herliyana, Desy Mulyosari, Imam Busyra Abdillah, Rohmah Pari and Salim Hiziroglu

Appl. Sci. **2020**, *10*(17), 6101; https://doi.org/10.3390/app10176101 - 02 Sep 2020

Abstract In general fast-growing tree species harvested at a young age has substantial amount of sapwood. It also contains juvenile wood, which has undesirable inferior physical and mechanical properties. Having sapwood and juvenile wood in the trees makes them very susceptible to be attacked [...] Read more.

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by Danica Kačíková, Ivan Kubovský, Nikoleta Ulbriková and František Kačík

Appl. Sci. **2020**, *10*(14), 5021; https://doi.org/10.3390/app10145021 - 21 Jul 2020

Abstract Thermal modification is an environmentally friendly method to improve dimensional stability, durability, and aesthetic properties of wood. Changes in lignin as one of the main wood components markedly influence wood product properties and recycling possibilities of thermowood at the end of its life [...] Read more.

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Fluid Flow in Nanosilver-Impregnated Heat-Treated Beech Wood in Different Mediums

by Hamid R. Taghiyari, Ghane Hosseini, Asghar Tarmian and Antonios N. Papadopoulos

Appl. Sci. **2020**, *10*(6), 1919; https://doi.org/10.3390/app10061919 - 11 Mar 2020

Abstract Specific gas permeability of beech wood was determined and compared with values obtained after nanosilver-impregnation and heat-treatment in three mediums of air, water, and water steam at 150 °C for four durations of 1, 2, 3, and 4 h. Separate sets of specimens [...] Read more.

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Open Access Review

Recent Developments in Lignin- and Tannin-Based Non-Isocyanate Polyurethane Resins for Wood Adhesives—A Review

by Manggar Arum Aristri, Muhammad Adly Rahandi Lubis, Sumit Manohar Yadav, Petar Antov, Antonios N. Papadopoulos, Antonio Pizzi, Widya Fatriasari, Maya Ismayati and Apri Heri Iswanto

Appl. Sci. **2021**, *11*(9), 4242; https://doi.org/10.3390/app11094242 - 07 May 2021

Abstract This review article aims to summarize the potential of using renewable natural resources, such as lignin and tannin, in the preparation of NIPUs for wood adhesives. Polyurethanes (PUs) are extremely versatile polymeric materials, which have been widely used in numerous applications, e.g., packaging, [...] Read more.

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Appl. Sci., Volume 10, Issue 20 (October-2 2020) – 377 articles

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by Mingyu Fu, Tan Zhang, Fuguang Ding and Duansong Wang
Appl. Sci. 2020, 10(20), 7381; https://doi.org/10.3390/app10207381 - 21 Oct 2020
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Abstract This paper develops a totally new appointed-time integral barrier Lyapunov function-based trajectory tracking algorithm for a hovercraft in the presence of multiple performance constraints and model uncertainties. Firstly, an appointed-time performance constraint function is skillfully designed, which proposes to pre-specify the a priori [...] Read more.
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Neovascularization Effects of Carbon Monoxide Releasing Drugs Chemisorbed on *Coscinodiscus* Diatoms Carriers Characterized by Spectromicroscopy Imaging

by Joachim Delasoie, Natasa Radakovic, Aleksandar Pavic and Fabio Zobi
Appl. Sci. 2020, 10(20), 7380; https://doi.org/10.3390/app10207380 - 21 Oct 2020
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Abstract Silica microparticles made of diatomaceous earth have become particularly attractive materials for designing drug delivery systems. In order to investigate the use of natural diatoms as drug scaffolds for carbon monoxide releasing molecules (CORMs), we evaluated the chemisorption of the cis-$[Re(CO)_2Br$ [...] Read more.
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Illegal Logging Detection Based on Acoustic Surveillance of Forest

by Iosif Mporas, Isidoros Perikos, Vasilios Kelefouras and Michael Paraskevas
Appl. Sci. 2020, 10(20), 7379; https://doi.org/10.3390/app10207379 - 21 Oct 2020
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Abstract In this article, we present a framework for automatic detection of logging activity in forests using audio recordings. The framework was evaluated in terms of logging detection classification performance and various widely used classification methods and algorithms were tested. Experimental setups, using different [...] Read more.
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by David Vallejo, Cristian Gmez-Portes, Javier Albusac, Carlos Glez-Morcillo and José Jesús Castro-Schez
Appl. Sci. 2020, 10(20), 7378; https://doi.org/10.3390/app10207378 - 21 Oct 2020
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Abstract Physical rehabilitation of stroke patients is based on the daily execution of exercises with face-to-face supervision by therapists. This model cannot be sustained in the long term, due to the involved economic costs, the growing number of patients, and the aging population. Remote [...] Read more.
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Seismic Behavior of a Bridge with New Composite Tall Piers under Near-Fault Ground Motion Conditions

by Zhehan Cai, Zhijian Wang, Kaiqi Lin, Ying Sun and Weidong Zhuo
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Abstract Currently, the seismic designs of reinforced concrete (RC) bridges with tall piers are often accomplished following the ductility-based seismic design method. Though the collapses of the RC bridges with tall piers can be avoided, they are likely to experience major damage and loss [...] Read more.
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by Diangeng Li, Zicheng Zhang, Shifei Liu and Song Li
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Abstract In liquid mediums, whether the breakdown strength can be greatly improved after introducing the nano-particles has been widely investigated, however, there has been no scientific consensus on the modification mechanism of this anomalous phenomenon. In this paper, we first experimentally measured the streamer [...] Read more.
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Effect of Wing Corrugation on the Aerodynamic Efficiency of Two-Dimensional Flapping Wings

by Thanh Tien Dao, Thi Kim Loan Au, Soo Hyung Park and Hoon Cheol Park
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Abstract Many previous studies have shown that wing corrugation of an insect wing is only structurally beneficial in enhancing the wing's bending stiffness and does not much help to improve the aerodynamic performance of flapping wings. This study uses two-dimensional computational fluid dynamics (CFD) [...] Read more.
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Antidepressant-Like Effects of Ethanol Extract of *Ziziphus jujuba* Mill Seeds in Mice

by Jong Min Oh, Moongi Ji, Mi-Jin Lee, Geum Seok Jeong, Man-Jeong Paik, Hoon Kim and Joo-Won Suh
Appl. Sci. 2020, 10(20), 7374; https://doi.org/10.3390/app10207374 - 21 Oct 2020
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Abstract The antidepressant-like activity of ethanol extract of *Ziziphus jujuba* Mill var. *spinosa* seeds (Semen Ziziphi Spinosae, SZS) was investigated by behavioral tests, such as a forced swimming test (FST), a tail-suspension test (TST), and an open field test (OFT), using mice exposed to [...] Read more.
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Physiological Characterization of a Novel Wild-Type *Yarrowia lipolytica* Strain Grown on Glycerol: Effects of Cultivation Conditions and Mode on Polyols and Citric Acid Production

by Seraphim Papanikolaou, Panagiota Diamantopoulou, Fabrice Blanchard, Eleni Lambrinea, Isabelle Chevalot, Nikolaos G. Stoforos and Emmanuel Rondags
Appl. Sci. 2020, 10(20), 7373; https://doi.org/10.3390/app10207373 - 21 Oct 2020
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Abstract A new yeast wild-type *Yarrowia lipolytica* isolate presented efficient growth on glycerol. During flask cultures, nitrogen limitation led to the secretion of sugar-alcohols as the major metabolites of the process (mannitol, arabitol and erythritol), whereas insignificant quantities of citrate were synthesized. Although in [...] Read more.
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by Hyeonjin Cha, Jaeyoung Lee, Hee Ho Park and Ju Hyun Park
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Abstract The generation of functional osteoblasts from human somatic cells could provide an alternative means of regenerative therapy for bone disorders such as osteoporosis. In this study, we demonstrated the direct phenotypic conversion of human dermal fibroblasts (HDFs) into osteoblasts by culturing them in [...] Read more.
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Methanol Production from Pyrolysis Oil Gasification—Model Development and Impacts of Operating Conditions

by Zhihai Zhang, Benoit Delcroix, Olivier Rezazgui and Patrice Mangin
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Abstract A novel process model simulating methanol production through pyrolysis oil gasification was developed, validated, then used to predict the effect of operating conditions on methanol production yield. The model comprised gasification, syngas post-treatment, and methanol synthesis units. The model was validated using experimental [...] Read more.
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by Vlad Fernoaga, Venetia Sandu and Titus Balan
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Abstract The actual trade-off among engine emissions and performance requires detailed investigations into exhaust system configurations. Correlations among engine data acquired by sensors are susceptible to artificial intelligence (AI)-driven performance assessment. The influence of exhaust back pressure (EBP) on engine performance, mainly on effective [...] Read more.
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by Jun Song, Brooke Pallas, Dongshan Yang, Jifeng Zhang, Yash Agarwal, Y. Eugene Chen, Moses Bility and Jie Xu
Appl. Sci. 2020, 10(20), 7369; https://doi.org/10.3390/app10207369 - 21 Oct 2020
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Abstract Production of immunodeficient (ID) models in non-murine animal species had been extremely challenging until the advent of gene-editing tools: first zinc finger nuclease (ZFN), then transcription activator-like effector nuclease (TALEN), and most recently clustered regularly interspaced short palindromic repeats-associated protein 9 (CRISPR)/Cas9. We [...] Read more.
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Sustainability Analysis of the M-30 Madrid Tunnels and Madrid Rio after 14 years of Service Life

by Lucía López-de Abajo, Ana Patricia Pérez-Fortes, Marcos G. Alberti, Jaime C. Gálvez and Tomás Ripa
Appl. Sci. 2020, 10(20), 7368; https://doi.org/10.3390/app10207368 - 21 Oct 2020
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Abstract In 2007, the excavation of the M-30 ring road located in Madrid and the creation of a green corridor either side of the Manzanares river brought significant change to the metropolitan area. The corridor and linear park which it provided were designed to [...] Read more.
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Identification of Bacterial and Fungal Communities in the Roots of Orchids and Surrounding Soil in Heavy Metal Contaminated Area of Mining Heaps

by Miroslav Böhmer, Daniel Ozdín, Matúš Račko, Michal Lichvár, Jaroslav Budiš and Tomáš Szemes
Appl. Sci. 2020, 10(20), 7367; https://doi.org/10.3390/app10207367 - 21 Oct 2020
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Abstract Orchids represent a unique group of plants that are well adapted to extreme conditions. In our study, we aimed to determine if different soil contamination and pH significantly change fungal and bacterial composition. We identified bacterial and fungal communities from the roots and [...] Read more.
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Economic Assessment of Solar-Powered Residential Battery Energy Storage Systems: The Case of Madeira Island, Portugal

by Lucas Pereira, Jonathan Cavaleiro and Luisa Barros
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Abstract This paper presents an economic assessment of introducing solar-powered residential battery energy storage in the Madeira Island electric grid, where only micro-production for self-consumption is currently allowed. The evaluation was conducted against six local micro-producers using one year of energy consumption and solar [...] Read more.
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Geophysical Characterization of Aquifers in Southeast Spain Using ERT, TDEM, and Vertical Seismic Reflection

by Javier Rey, Julián Martínez, Rosendo Mendoza, Senén Sandoval, Vladimir Tarasov, Alex Kaminsky, M. Carmen Hidalgo and Kevin Morales
Appl. Sci. 2020, 10(20), 7365; https://doi.org/10.3390/app10207365 - 21 Oct 2020
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Abstract We assess the effectiveness of complementary geophysical techniques to characterize a Jurassic dolomite confined aquifer at Loma de Ubeda, Spain. This aquifer, which is penetrated by wells in the 100–600-m depth range, is confined by Triassic clays (bottom) and Miocene marls (top). The [...] Read more.
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Parylene-Based Flexible Microelectrode Arrays for the Electrical Recording of Muscles and the Effect of Electrode Size

by Bong-Jun Choi, Ju-Hwan Kim, Woo-Jin Yang, Dong-Jun Han, Jaewon Park and Dong-Wook Park
Appl. Sci. 2020, 10(20), 7364; https://doi.org/10.3390/app10207364 - 21 Oct 2020
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Abstract Miniaturized flexible microelectrode arrays are desirable for small-area surface electromyography (sEMG) to detect the electrical activity generated by muscles in a specific area of the body. Here, we present a flexible 8-channel microelectrode array with electrodes of diameter 150–300 µm for small-area sEMG [...] Read more.
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by Lei Xu, Erkuo Yang, Yasong Wang, Changyun Li, Zhiru Chen and Guofa Mi
Appl. Sci. 2020, 10(20), 7363; https://doi.org/10.3390/app10207363 - 21 Oct 2020
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Abstract Ultra high-pressure sintering (UHPS) was used to prepare AA6061/SiCp composites with different contents and the effect of sintering temperatures on microstructure and mechanical properties was investigated in this study. The results showed that a uniform distribution of nano-SiC particles (N-SiCp) is obtained by [...] Read more.

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Improving a Cable Robot Recovery Strategy by Actuator Dynamics

by Giovanni Boschetti, Riccardo Minto and Alberto Trevisani

Appl. Sci. 2020, 10(20), 7362; https://doi.org/10.3390/app10207362 - 21 Oct 2020

Abstract Cable-driven parallel robots offer several benefits in terms of workspace size and design cost with respect to rigid-link manipulators. However, implementing an emergency procedure for these manipulators is not trivial, since stopping the actuators abruptly does not imply that the end-effector rests at [...] Read more.

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Framework for Incorporating Artificial Somatic Markers in the Decision-Making of Autonomous Agents

by Daniel Cabrera, Claudio Cubillos, Enrique Urra and Rafael Mellado

Appl. Sci. 2020, 10(20), 7361; https://doi.org/10.3390/app10207361 - 21 Oct 2020

Abstract The somatic marker hypothesis proposes that when a person faces a decision scenario, many thoughts arise and different "physical consequences" are fleetingly observable. It is generally accepted that affective dimension influences cognitive capacities. Several proposals for including affectivity within artificial systems have been [...] Read more.

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A Review of Sample and Hold Systems and Design of a New Fractional Algorithm

by Manuel Duarte Ortigueira and José Tenreiro Machado

Appl. Sci. 2020, 10(20), 7360; https://doi.org/10.3390/app10207360 - 21 Oct 2020

Abstract Digital systems require sample and hold (S&H) systems to perform the conversion from analog to digital and vice versa. Besides the standard zero and first order holds, we find in the literature other versions, namely the fractional and exponential order holds, involving parameters [...] Read more.

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Open Access Editorial

Applications of Medical Informatics and Data Analysis Methods

by Pentti Nieminen

Appl. Sci. 2020, 10(20), 7359; https://doi.org/10.3390/app10207359 - 21 Oct 2020

Abstract
The science of statistics contributes to the development and application of tools for the design, analysis, and interpretation of empirical medical studies [...] Full article

(This article belongs to the Special Issue Medical Informatics and Data Analysis) Printed Edition available

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Numerical Analysis of the CIRCE-HERO PLOFA Scenarios

by Moscardini Marigrazia, Galleni Francesco, Pucciarelli Andrea, Martelli Daniele and Forgione Nicola

Appl. Sci. 2020, 10(20), 7358; https://doi.org/10.3390/app10207358 - 21 Oct 2020

Abstract The present work deals with simulations carried out at the University of Pisa by using the System Thermal Hydraulics code RELAP5/Mod3.3 to support the experimental campaign conducted at the ENEA (Energia Nucleare ed Energie Alternative) Brasimone Research Centre on the CIRColazione Eutettico—Heavy liquid [...] Read more.

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Content Adaptation and Depth Perception in an Affordable Multi-View Display

by Iñigo Ezcurdia, Adriana Arregui, Oscar Ardaiz, Amalia Ortiz and Asier Marzo

Appl. Sci. 2020, 10(20), 7357; https://doi.org/10.3390/app10207357 - 21 Oct 2020

Abstract We present SliceView, a simple and inexpensive multi-view display made with multiple parallel translucent sheets that sit on top of a regular monitor; each sheet reflects different 2D images that are perceived cumulatively. A technical study is performed on the reflected and transmitted [...] Read more.

(This article belongs to the Special Issue Computer Graphics and Virtual Reality)

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Selective Plasma Etching of Polymer-Metal Mesh Foil in Large-Area Hydrogen Atmospheric Pressure Plasma

by Richard Krumpolec, Jana Jurmanová, Miroslav Zemánek, Jakub Kelar, Dušan Kováčik and Mirko Černák

Appl. Sci. 2020, 10(20), 7356; https://doi.org/10.3390/app10207356 - 21 Oct 2020

Abstract We present a novel method of surface processing of complex polymer-metal composite substrates. Atmospheric-pressure plasma etching in pure H_2, N_2, H_2/N_2 and air plasmas was used to fabricate flexible transparent composite poly(methyl methacrylate) (PMMA)-based polymer film/Ag-coated [...] Read more.

(This article belongs to the Special Issue Plasma: From Materials to Emerging Technologies)

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New Aspects of Socioeconomic Assessment of the Railway Infrastructure Project Life Cycle

by Vít Hromádka, Jana Korytárová, Eva Vítková, Herbert Seelmann and Tomáš Funk

Appl. Sci. 2020, 10(20), 7355; https://doi.org/10.3390/app10207355 - 21 Oct 2020

Abstract The paper deals with the issue of evaluation of socioeconomic impacts of occurrences emerging from railway infrastructure. The presented research results form part of a broader research subject focusing on the evaluation of the socioeconomic benefits of projects for the implementation of measures [...] Read more.

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Experimental Analysis on the Thermal Management of Lithium-Ion Batteries Based on Phase Change Materials

by Mingyi Chen, Siyu Zhang, Guoyang Wang, Jingwen Wang, Dongxu Ouyang, Xiangyang Wu, Luyao Zhao and Jian Wang

Appl. Sci. 2020, 10(20), 7354; https://doi.org/10.3390/app10207354 - 21 Oct 2020

Abstract Temperature is an important factor affecting the working efficiency and service life of lithium-ion battery (LIB). This study carried out the experiments on the thermal performances of Sanyo ternary and Sony $LiFePO_4$ batteries under different working conditions including extreme conditions, natural convection [...] Read more.

(This article belongs to the Special Issue Advanced Phase Change Materials for Thermal Storage)

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Special Issue on Advanced Methods for Seismic Performance Evaluation of Building Structures

by Sang Whan Han

Appl. Sci. 2020, 10(20), 7353; https://doi.org/10.3390/app10207353 - 21 Oct 2020

Abstract When an earthquake occurs, it causes great damage to a large area. Although seismic engineering continues to develop, it is reported that recently occurred earthquakes inflicted major damage to various structures and loss of human lives. Such earthquake damage occurs in high seismic [...] Read more.
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Challenging the Resin-Zirconia Interface by Thermal Cycling or Mechanical Load Cycling or Their Combinations

by Sung-Min Kwon, Young Kyung Kim and Tae-Yub Kwon
Appl. Sci. 2020, 10(20), 7352; https://doi.org/10.3390/app10207352 - 20 Oct 2020
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Abstract The purpose of this in vitro study was to evaluate the influence of mechanical load cycling (MLC), which simulated mastication, alone or combined with thermal cycling (TC), on the resin shear bond strength (SBS) to zirconia. Two resin cements (Panavia F2.0 and RelyX [...] Read more.
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Comparative Study on Exponentially Weighted Moving Average Approaches for the Self-Starting Forecasting

by Jaehong Yu, Seoung Bum Kim, Jinli Bai and Sung Won Han
Appl. Sci. 2020, 10(20), 7351; https://doi.org/10.3390/app10207351 - 20 Oct 2020
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Abstract Recently, a number of data analysists have suffered from an insufficiency of historical observations in many real situations. To address the insufficiency of historical observations, self-starting forecasting process can be used. A self-starting forecasting process continuously updates the base models as new observations [...] Read more.
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Development of Attached Cavitation at Very Low Reynolds Numbers from Partial to Super-Cavitation

by Florent Ravelet, Amélie Danlos, Farid Bakir, Kilian Croci, Sofiane Khelladi and Christophe Sarraf
Appl. Sci. 2020, 10(20), 7350; https://doi.org/10.3390/app10207350 - 20 Oct 2020
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Abstract The present study focuses on the inception, the growth, and the potential unsteady dynamics of attached vapor cavities into laminar separation bubbles. A viscous silicon oil has been used in a Venturi geometry to explore the flow for Reynolds numbers ranging from [...] Read more.
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AR Book-Finding Behavior of Users in Library Venue

by Chun-I Lee, Fu-Ren Xiao and Yi-Wen Hsu
Appl. Sci. 2020, 10(20), 7349; https://doi.org/10.3390/app10207349 - 20 Oct 2020
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Abstract ARKit and ARCore, key technologies in recent augmented reality (AR) development, have allowed AR to become more integrated in our lives. However, how effective AR is in an auxiliary role in venue guidance and how to collect the actual behaviors of users in [...] Read more.
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Influence of Recycled Precast Concrete Aggregate on Durability of Concrete's Physical Processes

by F. Fiol, C. Thomas, J. M. Manso and I. López
Appl. Sci. 2020, 10(20), 7348; https://doi.org/10.3390/app10207348 - 20 Oct 2020
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Abstract The research presented in this article analysed the influence of incorporating precast concrete waste as an alternative to coarse aggregate in self-compacting concrete to generate new precast elements. The experimental study involved the characterization of recycled aggregate and the design of the mix [...] Read more.
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Inference of Drawing Elements and Space Usage on Architectural Drawings Using Semantic Segmentation

by Jinyo Seo, Hyejin Park and Seungyeon Choo
Appl. Sci. 2020, 10(20), 7347; https://doi.org/10.3390/app10207347 - 20 Oct 2020
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Abstract Artificial intelligence presents an optimized alternative by performing problem-solving knowledge and problem-solving processes under specific conditions. This makes it possible to creatively examine various design alternatives under conditions that satisfy the functional requirements of the building. In this study, in order to develop [...] Read more.
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Automatic Bridge Design Parameter Extraction for Scan-to-BIM

by Jae Hyuk Lee, Jeong Jun Park and Hyungchul Yoon
Appl. Sci. 2020, 10(20), 7346; https://doi.org/10.3390/app10207346 - 20 Oct 2020
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Abstract Building information modeling (BIM), which can efficiently manage the life cycle of structures, has been increasingly applied in the construction industry. However, it is difficult to implement BIM for existing structures, due to the differences between the design and as-built conditions. Point cloud [...] Read more.
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Offensive and Defensive Plus–Minus Player Ratings for Soccer

by Lars Magnus Hvattum
Appl. Sci. 2020, 10(20), 7345; https://doi.org/10.3390/app10207345 - 20 Oct 2020
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Abstract Rating systems play an important part in professional sports, for example, as a source of entertainment for fans, by influencing decisions regarding tournament seedings, by acting as qualification criteria, or as decision support for bookmakers and gamblers. Creating good ratings at a team [...] Read more.
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Special Equipment Safety Supervision System Architecture Based on Blockchain Technology

by Zhipeng Liang, Keping Zhou, Rugao Gao and Kaixin Gao
Appl. Sci. 2020, 10(20), 7344; https://doi.org/10.3390/app10207344 - 20 Oct 2020
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Abstract With the use of the traditional safety supervision system of special equipment, the job burnout of supervision participants and other supervision problems emerge endlessly, which leads to the supervision for the prevention of safety accidents being greatly weakened. In recent years, the significance [...] Read more.
(This article belongs to the Section Earth Sciences and Geography)
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The Novel Quantitative Assay for Measuring the Antibiofilm Activity of Volatile Compounds

(AntiBioVol)

by Malwina Brożyna, Anna Żywicka, Karol Fijałkowski, Damian Gorczyca, Monika Oleksy-Wawrzyniak, Karolina Dydak, Paweł Migdał, Bartłomiej Dudek, Marzenna Bartoszewicz and Adam Junka
Appl. Sci. 2020, 10(20), 7343; https://doi.org/10.3390/app10207343 - 20 Oct 2020
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Abstract Herein, we present a new test, dubbed AntiBioVol, to be used for the quantitative evaluation of antibiofilm activity of volatile compounds in vitro. AntiBioVol is performed in two 24-well plates using a basic microbiological laboratory equipment. To demonstrate AntiBioVol usability, we have scrutinized [...] Read more.
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Improving Low Frequency Isolation Performance of Optical Platforms Using Electromagnetic Active-Negative-Stiffness Method

by Yamin Zhao, Junning Cui, Junchao Zhao, Xingyuan Bian and Limin Zou
Appl. Sci. 2020, 10(20), 7342; https://doi.org/10.3390/app10207342 - 20 Oct 2020
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Abstract To improve the low-frequency isolation performance of optical platforms, an electromagnetic active-negative-stiffness generator (EANSG) was proposed, using nano-resolution laser interferometry sensors to monitor the micro-vibration of an optical platform, and precision electromagnetic actuators integrated with a relative displacement feedback strategy to counteract the [...] Read more.

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Dietary Patterns and Nutritional Status in Relation to Consumption of Chickpeas and Hummus in the U.S. Population

by Cara L. Frankenfeld and Taylor C. Wallace
Appl. Sci. 2020, 10(20), 7341; https://doi.org/10.3390/app10207341 - 20 Oct 2020
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Abstract Chickpeas, a commonly consumed legume, are the main ingredient in traditional hummus. U.S. dietary guidelines recommend consuming 1–1.5 cups of legumes per week. This study aimed to evaluate temporal changes in hummus and chickpea consumption and describe diet and biomarkers of health in [...] Read more.
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An Enhanced Adaptive Block Truncation Coding with Edge Quantization Scheme

by Ching-Nung Yang, Yung-Chien Chou, Tao-Ku Chang and Cheonshik Kim
Appl. Sci. 2020, 10(20), 7340; https://doi.org/10.3390/app10207340 - 20 Oct 2020
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Abstract Recently, image compression using adaptive block truncation coding based on edge quantization (ABTC-EQ) was proposed by Mathews and Nair. Their approach deals with an image for two types of blocks, edge blocks and non-edge blocks. Different from using the bi-clustering approach on all [...] Read more.
(This article belongs to the Special Issue Research on Multimedia Systems)

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High Accuracy Modeling for Solar PV Power Generation Using Noble BD-LSTM-Based Neural Networks with EMA

by Youngil Kim, Keunjoo Seo, Robert J. Harrington, Yongju Lee, Hyeok Kim and Sungjin Kim
Appl. Sci. 2020, 10(20), 7339; https://doi.org/10.3390/app10207339 - 20 Oct 2020
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Abstract More accurate self-forecasting not only provides a better-integrated solution for electricity grids but also reduces the cost of operation of the entire power system. To predict solar photovoltaic (PV) power generation (SPVG) for a specific hour, this paper proposes the combination of a [...] Read more.
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A Taxonomy for Security Flaws in Event-Based Systems

by Youn Kyu Lee and Dohoon Kim
Appl. Sci. 2020, 10(20), 7338; https://doi.org/10.3390/app10207338 - 20 Oct 2020
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Abstract Event-based system (EBS) is prevalent in various systems including mobile cyber physical systems (MCPSs), Internet of Things (IoT) applications, mobile applications, and web applications, because of its particular communication model that uses implicit invocation and concurrency between components. However, an EBS's non-determinism in [...] Read more.
(This article belongs to the Special Issue Trustworthiness in Mobile Cyber Physical Systems)

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Open Access Review

Treatment Strategy of Transarterial Chemoembolization for Hepatocellular Carcinoma

by Shiro Miyayama
Appl. Sci. 2020, 10(20), 7337; https://doi.org/10.3390/app10207337 - 20 Oct 2020
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Abstract Transarterial chemoembolization (TACE) is a first-line treatment for patients with hepatocellular carcinoma (HCC) in Barcelona Clinic Liver Cancer stage B (BCLC-B). There are two major techniques of TACE: conventional TACE (cTACE) using iodized oil and gelatin sponge particles, and TACE using drug-eluting beads [...] Read more.
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Monitoring Land Cover Change on a Rapidly Urbanizing Island Using Google Earth Engine

by Lili Lin, Zhenbang Hao, Christopher J. Post, Elena A. Mikhailova, Kunyong Yu, Liuqing Yang and Jian Liu
Appl. Sci. 2020, 10(20), 7336; https://doi.org/10.3390/app10207336 - 20 Oct 2020
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Abstract Island ecosystems are particularly susceptible to climate change and human activities. The change of land use and land cover (LULC) has considerable impacts on island ecosystems, and there is a critical need for a free and open-source tool for detecting land cover fluctuations [...] Read more.
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Applying the Cracking Elements Method for Analyzing the Damaging Processes of Structures with Fissures

by Qianqian Dong, Jiu Wu, Zizhong Sun, Xiao Yan and Yiming Zhang
Appl. Sci. 2020, 10(20), 7335; https://doi.org/10.3390/app10207335 - 20 Oct 2020
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Abstract In this work, the recently proposed cracking elements method (CEM) is used to simulate the damage processes of structures with initial imperfections. The CEM is built within the framework of the conventional finite element method (FEM) and is formally similar to a special [...] Read more.
(This article belongs to the Special Issue Computational Methods for Fracture II)

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Effect of Cu, Cr, S Doped TiO_2 for Transparent Plastic Bar Reinforced Concrete

by Seung-Hoon Seo and Byoung-Il Kim
Appl. Sci. 2020, 10(20), 7334; https://doi.org/10.3390/app10207334 - 20 Oct 2020
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Abstract In this study, after firing and powdering Cu, Cr, and S with NP-400 TiO_2, an NO_x removal rate test was performed according to the ISO test method to analyze the photocatalytic reactivity in visible light. The distribution of the photocatalyst [...] Read more.
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Power Flow Analysis on the Dual Input Transmission Mechanism of Small Wind Turbine Systems

by Ah-Der Lin, Tsung-Pin Hung, Jao-Hwa Kuang and Hsiu-An Tsai

Appl. Sci. 2020, 10(20), 7333; https://doi.org/10.3390/app10207333 - 20 Oct 2020

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Abstract A parallel planetary gear train design is proposed to construct the wind turbine system that has double inputs and one output. The proposed system is flexible for the application, which may use a combination of two rotors, as used for horizontal axis or [...] Read more.

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Optimization of Parameters and Methodology for the Synthesis of LTA-Type Zeolite Using Light Coal Ash

by Thiago J. T. Cruz, Mariele I. S. Melo and Sibele Pergher

Appl. Sci. 2020, 10(20), 7332; https://doi.org/10.3390/app10207332 - 20 Oct 2020

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Abstract The synthesis of zeolites using waste as a source of Si and Al is well known, and light coal ash has been studied to minimize the problems of waste management and mitigate environmental effects. The residue used in this work was supplied by [...] Read more.

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A Study of High-Efficiency Laser Headlight Design Using Gradient-Index Lens and Liquid Lens

by Yi-Chin Fang, Yih-Fong Tzeng, Chan-Chuan Wen, Chao-Hsien Chen, Hsiao-Yi Lee, Shun-Hsyung Chang and Yi-Lun Su

Appl. Sci. 2020, 10(20), 7331; https://doi.org/10.3390/app10207331 - 20 Oct 2020

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Abstract In the field of vehicle lighting, due to the diode laser, its small size and high energy conversion efficiency, it can be effectively used as the headlight source of high beam. In recent years, it was adopted by European advanced car manufacturers as [...] Read more.

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A Comparative Study of Random Forest and Genetic Engineering Programming for the Prediction of Compressive Strength of High Strength Concrete (HSC)

by Furqan Farooq, Muhammad Nasir Amin, Kaffayatullah Khan, Muhammad Rehan Sadiq, Muhammad Faisal Javed, Fahid Aslam and Rayed Alyousef

Appl. Sci. 2020, 10(20), 7330; https://doi.org/10.3390/app10207330 - 20 Oct 2020

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Abstract Supervised machine learning and its algorithm is an emerging trend for the prediction of mechanical properties of concrete. This study uses an ensemble random forest (RF) and gene expression programming (GEP) algorithm for the compressive strength prediction of high strength concrete. The parameters [...] Read more.

(This article belongs to the Special Issue Green Concrete for a Better Sustainable Environment II)

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Nanocomposites Photocatalysis Application for the Purification of Phenols and Real Olive Mill Wastewater through a Sequential Process

by Srikanth Vuppala and Marco Stoller

Appl. Sci. 2020, 10(20), 7329; https://doi.org/10.3390/app10207329 - 20 Oct 2020

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Abstract In this study, a synthetic phenol solution of water and raw olive mill wastewater (OMW) were considered to achieve purification of the aqueous streams from pollutants. Only OMW was initially submitted to a coagulation/flocculation process, to reduce the turbidity, phenols, and chemical oxygen [...] Read more.

(This article belongs to the Special Issue Wastewater Bioremediation)

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Safety Concept for Textile-Reinforced Concrete Structures with Bending Load

by Sergej Rempel, Marcus Ricker and Josef Hegger

Appl. Sci. 2020, 10(20), 7328; https://doi.org/10.3390/app10207328 - 20 Oct 2020

Viewed by 437

Abstract In most countries, for the production and execution of concrete structures with textile reinforcement, building owners must have a general approval (e.g., "abZ" in Germany) or an individual license (e.g., "ZiE" in Germany). Therefore, it is quite common for building authorities to request [...] Read more.

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Influence of Radar and Gauge Rainfall Data Sources on the Analysis of Spatial Distribution of Traffic Accidents and Rainfall Events

by Seong-Sim Yoon, Un Ji and Inhyeok Bae

Appl. Sci. 2020, 10(20), 7327; https://doi.org/10.3390/app10207327 - 20 Oct 2020

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Abstract The records of 24,797 traffic accidents (9039 involving fatalities or severe injury) during rainy conditions from 2007 to 2017 in Seoul, South Korea, were used to analyze the spatial distribution of the traffic accidents and rainfall events based on radar and gauge rainfall [...] Read more.

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Image Analysis Applications for Building Inter-Story Drift Monitoring

by Yuan-Sen Yang, Qiang Xue, Pin-Yao Chen, Jian-Huang Weng, Chi-Hang Li, Chien-Chun Liu, Jing-Syu Chen and Chao-Tsun Chen

Appl. Sci. 2020, 10(20), 7304; https://doi.org/10.3390/app10207304 - 20 Oct 2020

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Abstract Structural health monitoring techniques have been applied to several important structures and infrastructure facilities, such as buildings, bridges, and power plants. For buildings, accelerometers are commonly used for monitoring the accelerations induced by ambient vibration to analyze the structural natural frequencies for further [...] Read more.

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Plant-Growth-Promoting Bacteria Mitigating Soil Salinity Stress in Plants

by Stefan Shilev

Appl. Sci. 2020, 10(20), 7326; https://doi.org/10.3390/app10207326 - 19 Oct 2020

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Abstract Soil deterioration has led to problems with the nutrition of the world's population. As one of the most serious stressors, soil salinization has a negative effect on the quantity and quality of agricultural production, drawing attention to the need for environmentally friendly technologies [...] Read more.

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An Approach to the Creation and Presentation of Reference Gesture Datasets, for the Preservation of Traditional Crafts

by Nikolaos Partarakis, Xenophon Zabulis, Antonis Chatziantoniou, Nikolaos Patsiouras and Ilia Adami

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Synthesis and Characterization of Spherical Calcium Carbonate Nanoparticles Derived from Cockle Shells

by Abbas Ibrahim Hussein, Zuryati Ab-Ghani, Ahmad Nazeer Che Mat, Nur Atikah Ab Ghani, Adam Husein and Ismail Ab. Rahman

Appl. Sci. 2020, 10(20), 7170; https://doi.org/10.3390/app10207170 - 14 Oct 2020

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Abstract Cockle shells are a natural reservoir of calcium carbonate ($CaCO_3$), which is widely used in bone repair, tissue scaffolds, and the development of advanced drug delivery systems. Although many studies report on the preparation of $CaCO_3$, the development of [...] Read more.

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Air Changes for Healthy Indoor Ambiences under Pandemic Conditions and Its Energetic Implications: A Galician Case Study

by José A. Orosa, Modeste Kameni Nematchoua and Sigrid Reiter

Appl. Sci. 2020, 10(20), 7169; https://doi.org/10.3390/app10207169 - 14 Oct 2020

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Abstract The present paper aims to show a mathematical understanding of the effect of ventilation rate over building energy consumption. Moreover, as a case study to show this methodology, a proposal was analyzed of modifying the teaching period to reach a maximum increase of [...] Read more.

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Partial Retraining Substitute Model for Query-Limited Black-Box Attacks

by Hosung Park, Gwonsang Ryu and Daeseon Choi

Appl. Sci. 2020, 10(20), 7168; https://doi.org/10.3390/app10207168 - 14 Oct 2020

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Abstract Black-box attacks against deep neural network (DNN) classifiers are receiving increasing attention because they represent a more practical approach in the real world than white box attacks. In black-box environments, adversaries have limited knowledge regarding the target model. This makes it difficult to [...] Read more.

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Experimental Investigation on Glaze Ice Accretion and Its Influence on Aerodynamic Characteristics of Pipeline Suspension Bridges

by Haiyan Yu, Fuyou Xu, Mingjie Zhang and Aoqiu Zhou

Appl. Sci. 2020, 10(20), 7167; https://doi.org/10.3390/app10207167 - 14 Oct 2020

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Abstract Pipeline suspension bridges may experience ice accretion under special atmospheric conditions, and the aerodynamic characteristics of the bridges may be modified by the ice accretion. Under some specific climatic conditions of freezing rain, the dependencies of the ice size and shape on the [...] Read more.

(This article belongs to the Special Issue Advances on Structural Engineering, Volume II)

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Seebeck–Peltier Transition Approach to Oncogenesis

by Umberto Lucia and Giulia Grisolia

Appl. Sci. 2020, 10(20), 7166; https://doi.org/10.3390/app10207166 - 14 Oct 2020

Cited by 1 | Viewed by 342

Abstract In this paper, a non-equilibrium thermodynamic approach to cancer is developed. The thermo-electric effects in the cell membrane are analysed, in relation to the Seebeck-like and the Peltier-like effects. The role of the cell membrane electric potential is studied from a thermodynamic viewpoint. [...] Read more.

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Bone Healing Evaluation Following Different Osteotomic Techniques in Animal Models: A Suitable Method for Clinical Insights

by Alexandra Anesi, Mattia Di Bartolomeo, Arrigo Pellacani, Marzia Ferretti, Francesco Cavani, Roberta Salvatori, Riccardo Nocini, Carla Palumbo and Luigi Chiarini

Appl. Sci. 2020, 10(20), 7165; https://doi.org/10.3390/app10207165 - 14 Oct 2020

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Abstract Osteotomy is a common step in oncological, reconstructive, and trauma surgery. Drilling and elevated temperature during osteotomy produce thermal osteonecrosis. Heat and associated mechanical damage during osteotomy can impair bone healing, with consequent failure of fracture fixation or dental implants. Several ex vivo [...] Read more.

(This article belongs to the Special Issue Bone Histogenesis and Regeneration)

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Naming in Multichannel with Beeps in the Strong Model

by Layla S. Aldawsari and Tom Altman

Appl. Sci. 2020, 10(20), 7164; https://doi.org/10.3390/app10207164 - 14 Oct 2020

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Abstract In this paper, a system of anonymous processes is considered that communicates with beeps through multiple channels in a synchronous communication model. In beeping channels, processes are limited to hearing either a beep or a silence from the channel with no collision detection. [...] Read more.

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Simple Approximate Formulas for Postbuckling Deflection of Heavy Elastic Columns

by Hiroyuki Shima

Appl. Sci. 2020, 10(20), 7163; https://doi.org/10.3390/app10207163 - 14 Oct 2020

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Abstract Columnar buckling is a ubiquitous phenomenon that occurs in both living things and man-made objects, regardless of the length scale ranging from macroscopic to nanometric structures. In general, analyzing the post-buckling behavior of a column requires the application of complex mathematical methods because [...] Read more.

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Assessment of Terrorism Risk to Critical Infrastructures: The Case of a Power-Supply Substation

by Xijun Yao, Hsi-Hsien Wei, Igal M. Shohet and Miroslaw J. Skibniewski

Appl. Sci. 2020, 10(20), 7162; https://doi.org/10.3390/app10207162 - 14 Oct 2020

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Abstract This paper presents a novel approach for estimating the vulnerability level of critical infrastructure confronting potential terrorist threats and assessing the usefulness of various protection strategies for critical infrastructure (CI). A methodology, utilizing a combination of topological network analysis and game theory, is [...] Read more.

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Multicriteria Autonomous Vehicle Control at Non-Signalized Intersections

by András Mihály, Zsófia Farkas and Péter Gáspár

Appl. Sci. 2020, 10(20), 7161; https://doi.org/10.3390/app10207161 - 14 Oct 2020

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Abstract The aim of the paper is to describe a multicriteria model predictive control method for autonomous vehicles at non-signalized intersections. The centralized controller aims to describe control action for each autonomous vehicle to guarantee collision free passage. At the same time, performances are [...] Read more.

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Soft Underwater Robot Actuated by Shape-Memory Alloys "JellyRobcib" for Path Tracking through Fuzzy Visual Control

by Christyan Cruz Ulloa, Silvia Terrile and Antonio Barrientos
Appl. Sci. 2020, 10(20), 7160; https://doi.org/10.3390/app10207160 - 14 Oct 2020
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Abstract Recent developments in bioinspired technologies combined with the advance of intelligent and soft materials have allowed soft robots to replicate the behavior of different animal species. These devices can perform complicated tasks such as reaching or adapting in constrained and unstructured environments. This [...] Read more.
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Constraints Hindering the Development of High-Rise Modular Buildings

by Yanhui Sun, Jun Wang, Jeremy Wu, Weixiang Shi, Dazhi Ji, Xiangyu Wang and Xianzhong Zhao
Appl. Sci. 2020, 10(20), 7159; https://doi.org/10.3390/app10207159 - 14 Oct 2020
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Abstract Off-site construction has been increasingly employed due to its advantages, for instance, improved quality control, reduced skills labour, faster construction time, decreased material wastage and safe working environment. As the most cutting-edge off-site construction, modular buildings have been utilised for residential building, student [...] Read more.
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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

by Muhtar
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Abstract Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete [...] Read more.
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Archetypal Use of Artificial Intelligence for Bridge Structural Monitoring

by Bernardino Chiaia and Valerio De Biagi
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Abstract Structural monitoring is a research topic that is receiving more and more attention, especially in light of the fact that a large part our infrastructural heritage was built in the Sixties and is aging and approaching the end of its design working life. [...] Read more.
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Heuristic Route Adjustment for Balanced Working Time in Urban Logistics with Driver Experience and Time-Dependent Traffic Information

by Tipaluck Krityakierne and Wasakorn Laesanklang
Appl. Sci. 2020, 10(20), 7156; https://doi.org/10.3390/app10207156 - 14 Oct 2020
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Abstract This article proposes a method to reduce working time violations of a real-world courier service in the urban logistics with time-dependent traffic information. The challenge is to reduce working time violation without creating significant changes to the urban logistics plan which provides city [...] Read more.
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Influence of Heterogeneous Catalysts and Reaction Parameters on the Acetylation of Glycerol to Acetin: A Review

by Usman Idris Nda-Umar, Irmawati Binti Ramli, Emee Noryana Muhamad, Norsahida Azri, Uchenna Fidelis Amadi and Yun Hin Taufiq-Yap
Appl. Sci. 2020, 10(20), 7155; https://doi.org/10.3390/app10207155 - 14 Oct 2020
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Abstract Glycerol, a polyhydric alcohol, is currently receiving greater attention worldwide in view of its glut in the market occasioned by the recent upsurge in biodiesel production. The acetylation of glycerol to acetin (acetyl glycerol) is one of the many pathways of upgrading glycerol [...] Read more.
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Semantic Mapping with Low-Density Point-Clouds for Service Robots in Indoor Environments

by Carlos Medina Sánchez, Matteo Zella, Jesús Capitán and Pedro J. Marrón
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Abstract The advancements in the robotic field have made it possible for service robots to increasingly become part of everyday indoor scenarios. Their ability to operate and reach defined goals depends on the perception and understanding of their surrounding environment. Detecting and positioning objects [...] Read more.
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A Machine Learning Framework for Assessing Seismic Hazard Safety of Reinforced Concrete Buildings

by Ehsan Harirchian, Vandana Kumari, Kirti Jadhav, Rohan Raj Das, Shahla Rasulzade and Tom Lahmer
Appl. Sci. 2020, 10(20), 7153; https://doi.org/10.3390/app10207153 - 14 Oct 2020
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Abstract Although averting a seismic disturbance and its physical, social, and economic disruption is practically impossible, using the advancements in computational science and numerical modeling shall equip humanity to predict its severity, understand the outcomes, and equip for post-disaster management. Many buildings exist amidst [...] Read more.
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Numerical Modeling of Surface Water and Groundwater Interactions Induced by Complex Fluvial Landforms and Human Activities in the Pingtung Plain Groundwater Basin, Taiwan

by Quoc-Dung Tran, Chuen-Fa Ni, I-Hsien Lee, Minh-Hoang Truong and Chien-Jung Liu
Appl. Sci. 2020, 10(20), 7152; https://doi.org/10.3390/app10207152 - 14 Oct 2020
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Abstract The landforms and human activities play important roles in quantifying surface water and groundwater interactions (SGIs) for water resources management. The study uses the groundwater and surface water flow (GSFLOW) model to quantify the dynamics of SGIs in the Pingtung Plain groundwater basin [...] Read more.
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Study of the Stiffness Characteristics of Waist Type Laminated Membrane Coupling

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by Miaomiao Li, Yinghao Zhao, Rupeng Zhu and Pingjun Li
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Abstract Studies show that the systematic study of the stiffness characteristics of the laminated membrane coupling is helpful to analyze the vibration status of the shaft system deeply and accurately. Moreover, such an investigation can provide a reliable guarantee for the safe operation of [...] Read more.
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Nonlinear Dynamics of a Cavity Containing a Two-Mode Coherent Field Interacting with Two-Level Atomic Systems

by E. M. Khalil, Hashim M. Alshehri, A.-B. A. Mohamed, S. Abdel-Khalek and A.-S. F. Obada
Appl. Sci. 2020, 10(20), 7150; https://doi.org/10.3390/app10207150 - 14 Oct 2020
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Abstract This study analytically explored two coupled two-level atomic systems (TLAS) as two qubits interacting with two modes of an electromagnetic field (EMF) cavity via two-photon transitions in the presence of dipole–dipole interactions between the atoms and intrinsic damping. Using special unitary su [...] Read more.
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Investigation of Mixed-Mode I/II Fracture under Impact Loading Using Split-Hopkinson Pressure Bar

by Fei Wang, Zheming Zhu, Meng Wang, Hao Qiu, Lei Zhou, Ruifeng Liu and Peng Ying
Appl. Sci. 2020, 10(20), 7149; https://doi.org/10.3390/app10207149 - 14 Oct 2020
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Abstract Mixed-mode fracture of construction building materials under impact loading is quite common in civil engineering. The investigation of mixed-mode crack propagation behavior is an essential work for fundamental research and engineering application. A variable angle single cleavage semi-circle (VASCSC) specimen was proposed with [...] Read more.
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by Vladas Kukėnas, Boris Khantonov, Mikhail Levinzon and Raimondas Jasevičius
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Abstract The JSC (Joint-Stock Company) "Railway Products Conformity Assessment Center", under a contract with JSC "Lithuanian Railways", carried out a rolling stock geometry and rolling surface defect risk assessment study which analyzed the principles and algorithm of the ATLAS-LG system used by JSC "Lithuanian [...] Read more.

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Relationship between Aspect Ratio and Crack Density in Porous-Cracked Rocks Using Experimental and Optimization Methods

by Hyung-Koo Yoon
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Abstract Aspect ratio and crack density are essential parameters to understand the physical properties of porous-cracked rocks, although it is difficult to independently determine each parameter, as both are closely linked. The objective of this study is to propose a relationship between aspect ratio [...] Read more.

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by Lucas D. L. da Silva, Thiago F. Pereira, Valderi R. Q. Leithardt, Laio O. Seman and Cesar A. Zeferino
Appl. Sci. 2020, 10(20), 7146; https://doi.org/10.3390/app10207146 - 14 Oct 2020
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Abstract Exoskeletons are wearable mobile robots that combine various technologies to enable limb movement with greater strength and endurance, being used in several application areas, such as industry and medicine. In this context, this paper presents the development of a hybrid control method for [...] Read more.
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Effect of Modifiers on the Rutting, Moisture-Induced Damage, and Workability Properties of Hot Mix Asphalt Mixtures

by Jiandong Huang and Yuantian Sun
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Abstract The present study aims to examine the effect of modifiers (Styrene-Butadiene-Styrene and crumb rubber) on the rutting, moisture-induced damage, and workability properties of hot mix asphalt (HMA) mixtures. In this study, three types—namely, control (CB), crumb rubber-modified (CRMB), and polymer-modified (PMB)—of mixtures/binders were [...] Read more.
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On the Use of Fuzzy and Permutation Entropy in Hand Gesture Characterization from EMG Signals: Parameters Selection and Comparison

by Alessandro Mengarelli, Andrea Tigrini, Sandro Fioretti, Stefano Cardarelli and Federica Verdini
Appl. Sci. 2020, 10(20), 7144; https://doi.org/10.3390/app10207144 - 14 Oct 2020
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Abstract The surface electromyography signal (sEMG) is widely used for gesture characterization; its reliability is strongly connected to the features extracted from sEMG recordings. This study aimed to investigate the use of two complexity measures, i.e., fuzzy entropy (FEn) and permutation entropy (PEn) for [...] Read more.
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Iterative Coordinate Reduction Algorithm of Flexible Multibody Dynamics Using a Posteriori Eigenvalue Error Estimation

by Seongji Han, Jin-Gyun Kim, Juhwan Choi and Jin Hwan Choi
Appl. Sci. 2020, 10(20), 7143; https://doi.org/10.3390/app10207143 - 14 Oct 2020
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Abstract Coordinate reduction has been widely used for efficient simulation of flexible multibody dynamics. To achieve the reduction of flexible bodies with reasonable accuracy, the appropriate number of dominant modes used for the reduction process must be selected. To handle this issue, an iterative [...] Read more.
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A Hybrid Approach Using GIS-Based Fuzzy AHP–TOPSIS Assessing Flood Hazards along the South-Central Coast of Vietnam

by Huu Xuan Nguyen, An Thinh Nguyen, Anh Tu Ngo, Van Tho Phan, Trong Doi Nguyen, Van Thanh Do, Dinh Cham Dao, Dinh Tung Dang, Anh Tuan Nguyen, The Kien Nguyen and Luc Hens
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Abstract Flood hazards affect the local economy and the livelihood of residents along the South-Central Coast of Vietnam

by Yeong-Cheol Heo, Kyuseok Kim and Youngjin Lee
Appl. Sci. 2020, 10(20), 7028; https://doi.org/10.3390/app10207028 - 10 Oct 2020
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Abstract The non-local means (NLM) noise reduction algorithm is well known as an excellent technique for removing noise from a magnetic resonance (MR) image to improve the diagnostic accuracy. In this study, we undertook a systematic review to determine the effectiveness of the NLM [...] Read more.
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Identification of Automotive Seat Rattle Noise Using an Independent Component Analysis-Based Coherence Analysis Technique

by Kookhyun Yoo and Un-Chang Jeong
Appl. Sci. 2020, 10(20), 7027; https://doi.org/10.3390/app10207027 - 10 Oct 2020
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Abstract This study proposed a contribution evaluation through the independent component analysis (ICA) method. The necessity of applying ICA to the evaluation of contribution was investigated through numerical simulation. Moreover, the estimation of the number of input sources, the labeling of signals, and the [...] Read more.
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Properties and Mechanism of Hydration of Fly Ash Belite Cement Prepared from Low-Quality Fly Ash

by Yongfan Gong, Cong Liu and Yanli Chen
Appl. Sci. 2020, 10(20), 7026; https://doi.org/10.3390/app10207026 - 10 Oct 2020
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Abstract Fly ash belite cement (FABC) is predominantly composed of α'_L-C_2S and $C_{12}A_7$. It is prepared from low-grade fly ashes by hydrothermal synthesis and low-temperature calcination methods. The formation, evolution process, and microstructure of FABC hydration [...] Read more.
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Abstract Humanity in the modern world is confronted with diverse problems at several levels. The environmental concern is probably the most important as it threatens different ecosystems, food, and farming as well as humans, animals, and plants. More specifically, salinization of agricultural soils is [...] Read more.
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by Kunpeng Jia, Xiaohan Wang, Jian Guo, Xin Ni, Gang Zhao, Zhenda Xie and Shining Zhu
Appl. Sci. 2020, 10(20), 7024; https://doi.org/10.3390/app10207024 - 10 Oct 2020
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Abstract Hyperparametric oscillation is essential for coherent optical signal generation in a broad wavelength range. Integration in a compact system, such a broadband light source, is of special interest for practical applications requiring field-deployable spectroscopy devices. Here we demonstrate an all-fiber hyperparametric oscillation source [...] Read more.
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by Sophia Karastogianni and Stella Girousi
Appl. Sci. 2020, 10(20), 7023; https://doi.org/10.3390/app10207023 - 09 Oct 2020
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Abstract Metabolic errors are inherited diseases, where genetic defects prevent a metabolic path, ending up in enzyme malfunction. In correspondence to its remaining or plenitude fall of enzymatic potency, there is an amassment of dangerous metabolites near the metabolic bar and/or a dearth of [...] Read more.
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Appl. Sci. 2020, 10(20), 7022; https://doi.org/10.3390/app10207022 - 09 Oct 2020
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Abstract The article considers industrial applications of digital twins and their contribution to decision-making and prevention of failures in manufacturing. Virtual laboratories are described as an example of using digital twins not only in industry but also for educational purposes. The article is also [...] Read more.
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A Secondary Reconfigurable Inverter and Its Control Strategy

by Yan Li, Peng Xiang and Yandong Chen
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Abstract This article proposes a topology of the secondary reconfigurable inverter and the corresponding fault-tolerant control strategy. When the secondary reconfigurable inverter is operating normally, its topology structure is the TPSS circuit. When the power semiconductor devices in the inverter are faulty, the inverter [...] Read more.
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Appl. Sci. 2020, 10(20), 7020; https://doi.org/10.3390/app10207020 - 09 Oct 2020
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Abstract One of the most widely used modalities of clinical imaging is computed tomography (CT). Recent reports of new contrast agents toward CT imaging have been numerous. The production of gold nanoparticles (AuNPs) as contrast agents for CT is primarily a topic of intense [...] Read more.
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Novel Gradation Design of Porous Asphalt Concrete with Balanced Functional and Structural Performances

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Abstract To improve the permeability of porous asphalt concrete (PAC) with a small nominal maximum aggregate size (NMAS) of 10 mm (PAC10), a novel gradation design by excluding the 0.075–3 mm aggregate was developed. This study aims to evaluate

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Effect of Environmental Temperature on the Insulating Performance of Epoxy/MgO Nanocomposites

by Guanghui Ge, Yongzhe Tang, Yuxia Li and Liangsong Huang
Appl. Sci. 2020, 10(20), 7018; https://doi.org/10.3390/app10207018 - 09 Oct 2020

Abstract This article reports on the development of nano-MgO/epoxy resin composites with various mass ratios via a solution blending method. The influence of MgO nanofillers on the thermal properties and the effect of environmental temperature on the insulating properties of the composite material were [...] Read more.
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Mechanistic Studies of Hydrogen Evolution Reaction on Donor-Acceptor Conjugated Polymer Photocatalysts

by Yves Ira A. Reyes, Li-Yu Ting, Xin Tu, Hsin-Yi Tiffany Chen, Ho-Hsiu Chou and Carmine Coluccini
Appl. Sci. 2020, 10(20), 7017; https://doi.org/10.3390/app10207017 - 09 Oct 2020

Abstract The application of donor-acceptor (D-A) conjugated polymer catalysts for hydrogen evolution reaction (HER) has shown great promise because of the tunability of such catalysts to have desired properties. Herein, we synthesized two polymer catalysts: poly[4,4'-(9-(4-aminophenyl)-9H-carbazole-3,6-diamine-alt-5-oxido-5-phenylbenzo[b]phosphindole-3,7-diyl)dibenzaldehyde] (PCzPO) and poly[N^1,N^1 [...] Read more.
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Appl. Sci. 2020, 10(20), 7016; https://doi.org/10.3390/app10207016 - 09 Oct 2020

Abstract Currently, data are a very valuable resource for organizations. Through analysis, it is possible to profile people or obtain knowledge about an event or environment and make decisions that help improve their quality of life. This concept takes on greater value in the [...] Read more.
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Appl. Sci. 2020, 10(20), 7015; https://doi.org/10.3390/app10207015 - 09 Oct 2020

Abstract Car tire manufacturing can be the cause of numerous environmental hazards. Harmful emissions from the production process are an acute danger to human health as well as the environment. To mitigate these unwanted consequences, manufacturers employ the eco-balance analysis at the product designing [...] Read more.
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Appl. Sci. 2020, 10(20), 7014; https://doi.org/10.3390/app10207014 - 09 Oct 2020

Abstract Electrohysterography (EHG) is a promising technique for pregnancy monitoring and preterm risk evaluation. It allows for uterine contraction monitoring as early as the 20th gestational week, and it is a non-invasive technique based on recording the electric signal of the uterine muscle activity [...] Read more.
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by Jamolbek Mattiev and Branko Kavsek
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Abstract Building accurate and compact classifiers in real-world applications is one of the crucial tasks in data mining nowadays. In this paper, we propose a new method that can reduce the number of class association rules produced by classical class association rule classifiers, while [...] Read more.
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Investigation on the Tip Positioning Accuracy of Cable-Driven Serpentine Manipulators

by Chutan Lin, Wenjing Zhang and Han Yuan
Appl. Sci. 2020, 10(20), 7012; https://doi.org/10.3390/app10207012 - 09 Oct 2020

Abstract Cable-driven serpentine manipulators (CDSMs), having strong compliance and flexibility, are suitable for flexible operation in confined workspace. Like many other manipulators, it is an important issue to sense the tip pose of CDSMs. In much previous research, the manipulator's tip pose is usually [...] Read more.
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On Applications of Spiking Neural P Systems

by Songhai Fan, Prithwineel Paul, Tianbao Wu, Haina Rong and Gexiang Zhang
Appl. Sci. 2020, 10(20), 7011; https://doi.org/10.3390/app10207011 - 09 Oct 2020

Abstract Over the years, spiking neural P systems (SNPS) have grown into a popular model in membrane computing because of their diverse range of applications. In this paper, we give a comprehensive summary of applications of SNPS and its variants, especially highlighting power systems [...] Read more.
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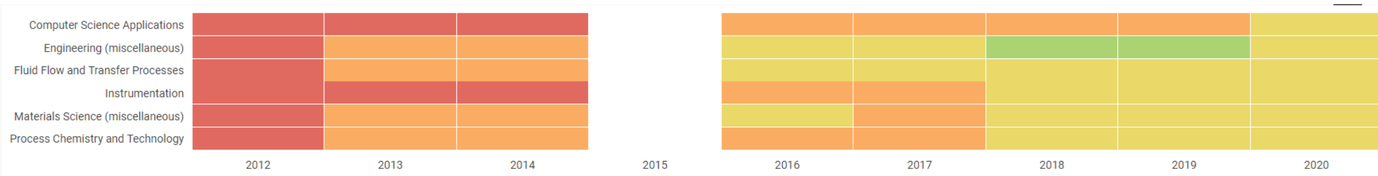

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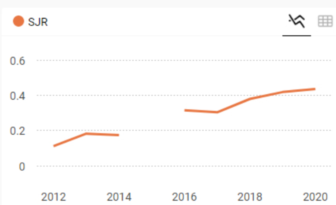

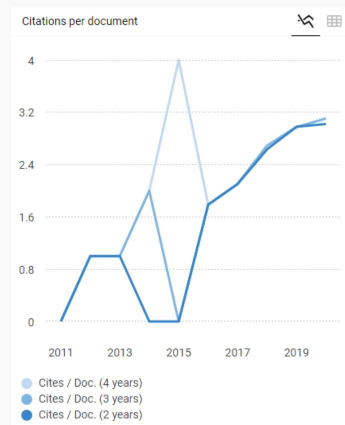

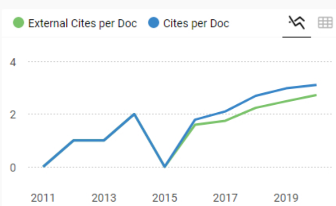

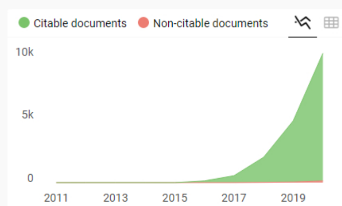

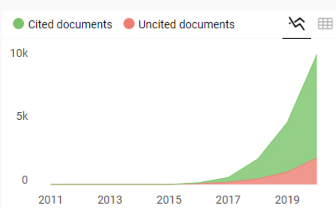

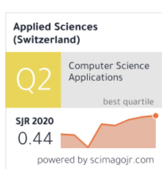

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Abstract: Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge were a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames were connected by four bridge beams. The bridge plate was made of a 10-cm-thick concrete plate. The bridge support of the reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus-type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm, meeting the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [2]. Bamboo is a renewable building material, such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboo, such as tensile strength, flexural strength, and other mechanical properties, can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3–4 years [3]. Bamboo is also very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures, such as warehouses, bridges, and village traditional houses, and for handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ±1500 species of bamboo [4]. In terms of its potential, in 2000 the total area of bamboo plants in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and 1,414,000 ha of bamboo plant areas outside forest areas [5]. Arsad (2015) [5] revealed that in the Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha, with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [6]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the petung bamboo (*Dendrocalamus asper*) and ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with a high tensile strength. The use of bamboo as concrete reinforcement for simple construction is applied specifically in underdeveloped village areas that have a lot of bamboo.

Bamboo for concrete reinforcement is because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the tensile stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. Bamboo is suitable for use in tensile elements, simple construction, such as roof trusses, simple bridge trusses, simple house construction elements, and so on. Muhtar et al. (2018) [7] tested the pull-out of bamboo reinforcement with a layer of Sikadur®-752 and hose clamps embedded in a concrete cylinder, showing an increase in tensile stress of up to 240% compared to untreated bamboo reinforced concrete (BRC). A single BRC beam with a bamboo reinforcing area ratio of 4% exceeds the ultimate load of a steel-reinforced concrete (SRC) beam by 38.54% with a steel reinforcement area ratio of 0.89% [8]. However, bamboo also has weaknesses, which are being easily attacked by insects and having high water absorption. This study did not test for fungal and insect attacks, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [2] and Stebbings (1904) [9], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aim to remove the starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength; however, after drying it undergoes a transition from a brittle behavior to a very resilient behavior [10]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [11], the content of bamboo fiber (BF) treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength. Moe Thwe (2003) [12] conducted a study on the durability of bamboo with treatment using calcium hydroxide (CaOH2) to increase flexibility and durability.

In this study, the technology used to prevent decay and absorption, and the effect of a high pH, is to provide a Sikadur adhesive that is also a waterproof layer, and the basis is previous research that has been conducted by several researchers, including (1) Ghavami (2005) [1], who researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel; (2) Agarwal et al. (2014) [13], who researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sikadur 32 Gel. From the sticky strength test, it was found that the best adhesive was the Sikadur 32 Gel; (3) Lima Jr et al. (2008) [14], who experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength or Young's Modulus; (4) Javadian et al. (2016) [15], who did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of a high pH on the strength properties will be carried out in future studies; and (5) Muhtar et al. (2019) [8], who processed bamboo reinforcement by immersing in water for 1 month, coating with Sikadur®-752, and applying a hose clamp. The pull-out test results show that the bond-stress increases by 200% when compared to untreated bamboo. Sikadur®-752 adhesive is quite effective in preventing the occurrence of hygroscopic and hydrolysis processes between bamboo and concrete. The non-adhesive hose-clamp does not affect bond stress.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include (1) Ghavami (2005) [1], who concluded that bamboo can be used as a structural concrete element, including beams, windows, frames, and elements that experience bending stress; (2) Agarwal et al. (2014) [13], who conducted tests of treated bamboo reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements; (3) Sakaray et al. (2012) [16], who conducted a feasibility test for the moso-type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete; (4) Nayak et al. (2013) [17], who conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is three times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement; (5) Kaware et al. (2013) [18], who reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel; (6) Khan (2014) [19], who researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo reinforced concrete can be used successfully for structural and non-structural elements in building construction; (7) Rahman et al. (2011) [3], who conducted tests on bamboo reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete; (8) Sethia and Baradiya (2014) [20], who in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams; (9) Terai and Minami (2011) [21], who conducted a study on 11 bamboo reinforced concrete beams and tested them to check for flexural cracks and shear cracks, and concluded that the crack pattern of bamboo reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel-reinforced concrete beams; and (10) Muhtar (2020) [22], who conducted a flexural test on four beams with untreated bamboo reinforcement and treated with Sikadur®-752 and a hose clamp. The test results showed that the beam treated with Sikadur®-752 increased the load capacity by 164% when compared to the untreated reinforced bamboo. With the first treatment, bamboo is suitable for use as a simple construction concrete reinforcement.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [8,23], drying in free air [3,13], applying a waterproof layer [24], and sprinkled with sand, to modify the roughness of the bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [25], Sikadur 32 Gel [1,13], and Sikadur®-752 [7,22–24,26,27]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond stress of bamboo reinforcement [23]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [28–31], bamboo as column reinforcement [17–34], bamboo as slab reinforcement or panel reinforcement [35–37], and bamboo as a bridge frame reinforcement [38,39].

Muhtar [22] tested the flexural properties of four types of bridge beams with different treatments. The size of the bridge beam is 120 mm × 200 mm × 2100 mm with the area of tensile reinforcement $\rho = 4.68\%$ and compressive reinforcement $\rho' = 1.88\%$. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of the bamboo reinforcement with adhesive, sand, and hose clamp can increase the bond stress and capacity of the bamboo reinforced concrete beam (BRC beam) [22]. The relationship between load vs. displacement is shown in Figure 1.

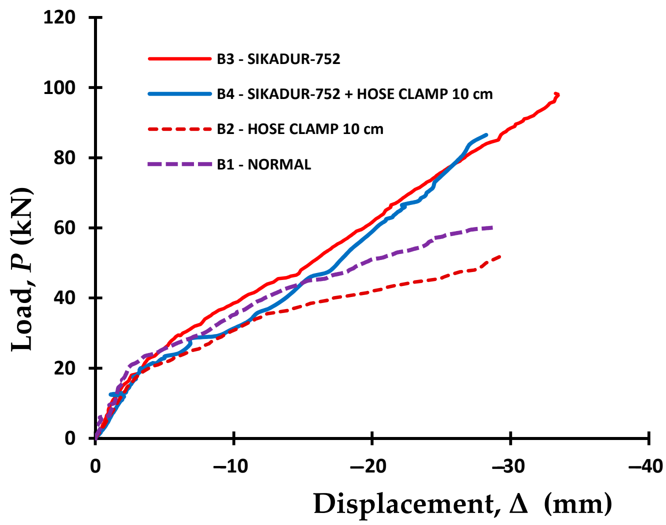


Figure 1. The relationship of load vs. deflection of the bamboo reinforced concrete (BRC) beam [22].

Testing of bridge trusses has been carried out by several researchers, including bamboo as reinforcement for a truss easel [39] and as reinforcement for a bridge frame with a span of 3 m [38]. Dewi and Wonlele [39] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of the support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength; however, the collapse pattern still shows a bending effect [39].

Muhtar et al. [38] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", and one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has a higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of the load (P) vs. deflection (Δ) of the two bridge frames is shown in Figure 2.

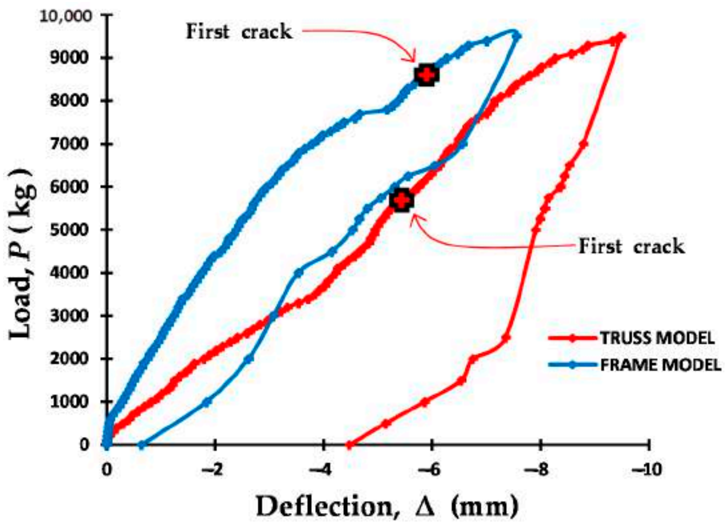


Figure 2. The relationship pattern of load vs. deflection of the bridge frame [38].

The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [22]. In this study, strengthening of the reinforcement with hose clamps is only for tensile reinforcement, whereas in previous studies it was carried out for all reinforcements. Hose-clamp strengthening when the distance is too close together can reduce the elastic properties of the bamboo and reduce its capacity. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [38]. The reinforcement model on the lower side frame stem is installed with the concept of flexural reinforcement, whereas in previous studies it was carried out with the concept of truss reinforcement or symmetry, and their behavior shows flexural behavior. The basis for using the results of previous laboratory research is to control the results of the direct tests in the field. The novelty that is expected is (1) obtaining a prototype of the precast concrete reinforced concrete bridge; and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. The expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement, which could be applied to a simple frame bridge structure in underdeveloped village areas with local materials that are cheap, environmentally friendly, and acceptable.

The targets to apply this research to are underdeveloped villages with lots of bamboos. Bamboo is a new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including for reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used was the petung bamboo (*Dendrocalamus asper*), aged 3–5 years [13,23]. For the petung bamboo, the bamboo shoots are purplish-black, covered with hairs that are velvety brown to blackish. Petung bamboo is large, with a segment length 40–50 cm, diameter 12–18 cm, and a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, as per Brink (2008) in Wikipedia Indonesia (2016) [2]. The mechanical properties of petung bamboo are shown in Table 1. The tensile test for bamboo petung was based on ASTM D 143-94 [40].

Table 1. Mechanical properties of petung bamboo [41].

Mechanical Properties	
Tensile strength (MPa)	105 ± 8
Modulus of elasticity (GPa)	26 ± 5
Elongation of fault (%)	16 ± 1
Flexural strength (MPa)	153 ± 11
Hardness (VHN)	5 ± 1
Impact strength (J/mm^2)	0.15 ± 0.7

The bamboo part that is taken was 6–7 m from the base of the bamboo stem. The bamboo was cut and split into a bamboo reinforcement size of 15 × 15 mm^2. The bamboo to be used must be treated with the following steps: (a) the bamboo must be cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm × 15 mm × 2000 mm for bridge beam reinforcement, and 15 mm × 15 mm × 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm × 15 mm × 1100 mm, the top stem is 15 mm × 15 mm × 1100 mm, and the diagonal stem is 15 mm × 15 mm × 1300 mm; (b) the bamboo must be soaked in water for 1–2 months to remove the sugar content and prevent termites and insects, as shown in Figure 3 [9]; (c) it should be dried in free air until the moisture content is approximately 12%, as shown in Figure 4; (d) the bamboo reinforcement should be trimmed with a grinding machine according to the specified size, as shown in Figure 5; (e) one should provide a waterproof layer to reduce the occurrence of the hydrolysis process between the bamboo and concrete, as shown in Figure 6;

(f) do sand sprinkling to modify the roughness of the bamboo reinforcement, as shown in Figure 7; and (g) stringing the bamboo reinforcement, as shown in Figure 8.

Ghavami (2005) [1] and Agarwal et al. (2014) [13] concluded that the best waterproof layer is Sikadur 32 Gel. Muhtar (2019) [8] treated bamboo with Sikadur®-752 and a hose clamp. The test results show that the adhesion strength increases up to 200% and the beam capacity increases 164% when compared to untreated bamboo reinforcement. The waterproof or adhesive layer used here was Sikadur®-752, produced by PT Sika Indonesia [8,27]. Sikadur®-752 is a solvent-free, two-component, super-low viscosity liquid, based on high strength epoxy resins—especially for injecting into the cavities and cracks in concrete. Usually used to fill and seal cavities and cracks in structural concrete, Sikadur®-752 is applied to the bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage. The thermal effect of Sikadur®-752 on bamboo reinforcement can be prevented by the moisture content of 12% in bamboo. In determining the strength of the bamboo, a 12% moisture content in the air-dry condition has been considered as a reference standard [42], and the temperature does not significantly affect the loss of stiffness [43]. Chemical treatment of bamboo helps increase the durability of the bamboo fibers and reduces the moisture absorption of the bamboo fibers [44].

Table 2. The specifications of Sikadur®-752 [45].

Components	Properties
Color	Yellowish
Density	Approx. 1.08 kg/L
Mixing Ratio, by weight/volume	2:1
Pot life at +30 °C	35 min
Compressive strength	62 N/mm^2 at 7 days (ASTM D-695) 64 N/mm^2 at 28 days
Tensile strength	40 N/mm^2 at 28 days (ASTM D-790)
Tensile adhesion strength	2 N/mm^2 (Concrete failure, over mechanically prepared concrete surface)
Coefficient of thermal expansion	−20 °C to +40 °C, 89 × 10^{-6} per °C
Modulus of elasticity	1060 N/mm^2

The hose clamp used had a diameter of $\frac{3}{4}$″, made in Taiwan [8,22]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm in diameter, with a f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of the bamboo (E_b) was 17,236 MPa, with a tensile strength of 127 N/mm^2 [8], and the modulus of steel elasticity (E_s) was 207,736 MPa [8]. The concrete mixture used was Portland Pozzolana Cement (PPC), with a pH of 7, as well as sand, coarse aggregate, and water with a mixed proportion of 1.81:2.82:0.52, as shown in Table 3. The average compressive strength of the concrete was 31.31 MPa at the age of 28 days. The process of treating the bamboo to assembling the bamboo reinforcement can be seen in Figures 3–8.

Table 3. The mix composition of the concrete.

The Concrete Mix Design	Cement (PPC)	Fine Aggregate	Coarse Aggregate	Water
	Kg/m^3			
Material per m^3	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

Figure 3. Take bamboo from the soaking.

Figure 4. Drying bamboo in free air.

Figure 5. Tidy up the bamboo according to size.

Figure 6. Give a waterproof coating.

Figure 7. Sand sprinkling on bamboo reinforcement.

Figure 8. Stringing the bamboo reinforcement.

2.2. Methods

The dimensions of the bridge were a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge was 280 cm. Two bridge frames were connected by four bridge beams. Each end of the bridge beam was connected to the knot point with two bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of the joints between the beam and precast bridge frame are shown in Figures 9 and 10. The bridge supports were made of reinforced concrete with the assumption of hinge support and a rubber bearing assuming roller support. The bridge plate was a 10-cm-thick concrete plate with 0.3-mm-thick spandex. The shape and model of the precast bridge of the bamboo reinforced concrete frame are described in Figure 11. Details of the reinforcement of the precast bridge beams are shown in Figure 12. Details of the reinforcement of the bridge frame are shown in Figures 13 and 14 and Table 4.

The design concept of the bamboo reinforced concrete beams follows Ghavami (2005) [1] and Muhtar (2020) [22], as shown in Figure 15. The balance of the concrete compressive force ($C = C_{b'} + Cc$) and the tensile force (T) must be met, as shown in Figure 15. The tensile strength of the bamboo reinforcement (T) was obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo reinforced concrete beams was due to the breaking of the bonds between the bamboo and concrete.

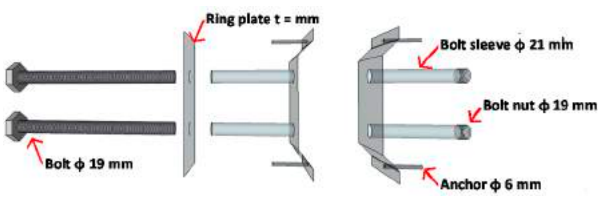
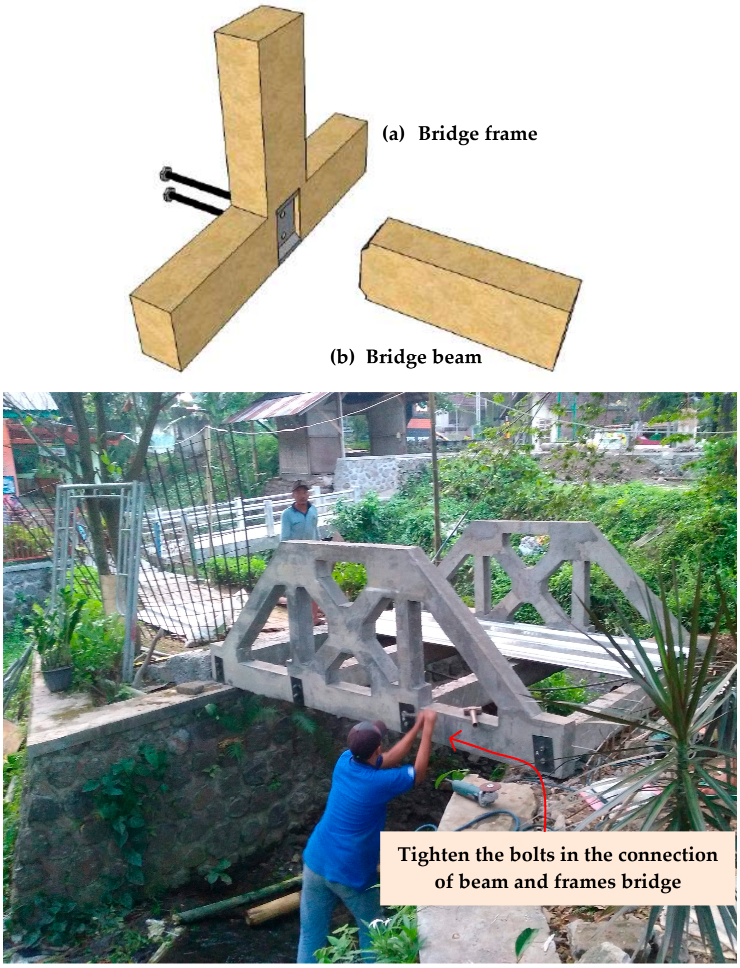


Figure 9. Details of the ring plate and bolt sleeve.



(c) Precast bridge frames

Figure 10. Models and applications of the precast connections.

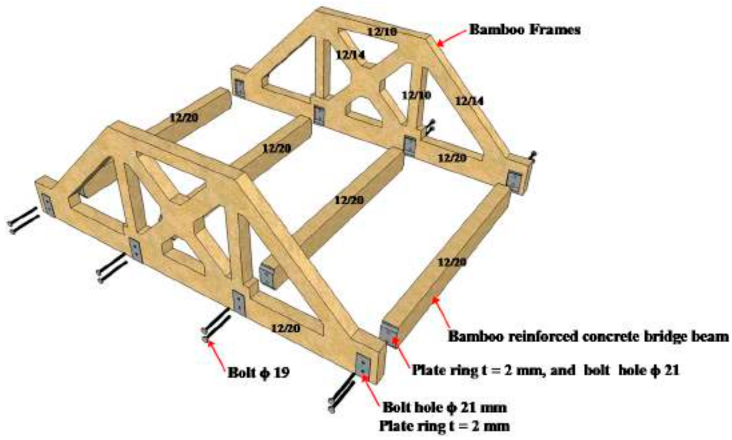


Figure 11. Model of the precast bridge made from bamboo reinforced concrete.

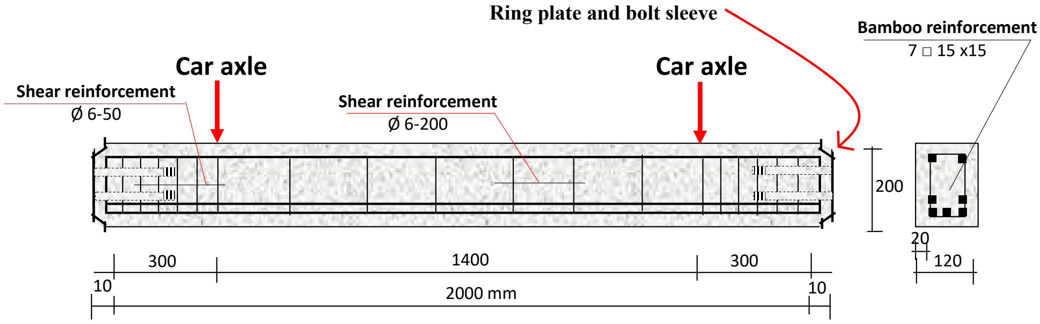


Figure 12. Details of the precast bridge beam reinforcement [22].

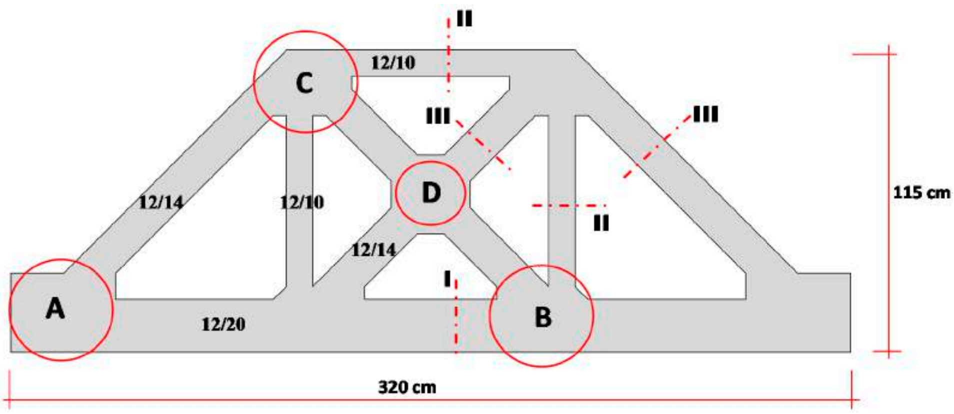


Figure 13. Details of the precast bridge frame [38].

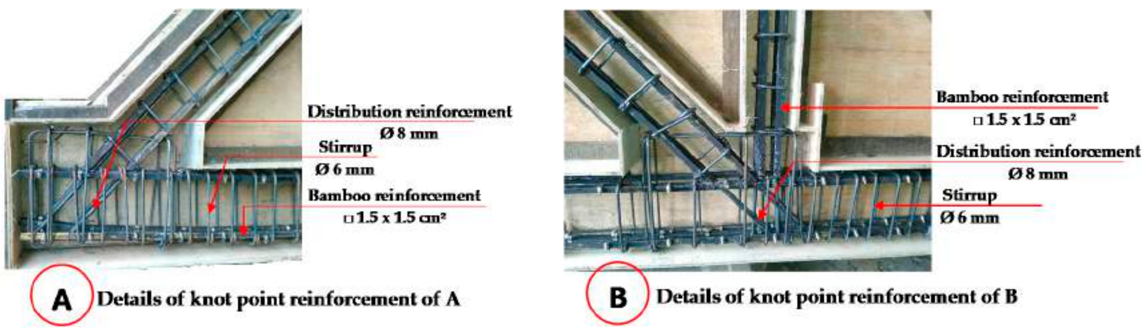


Figure 14. *Cont.*

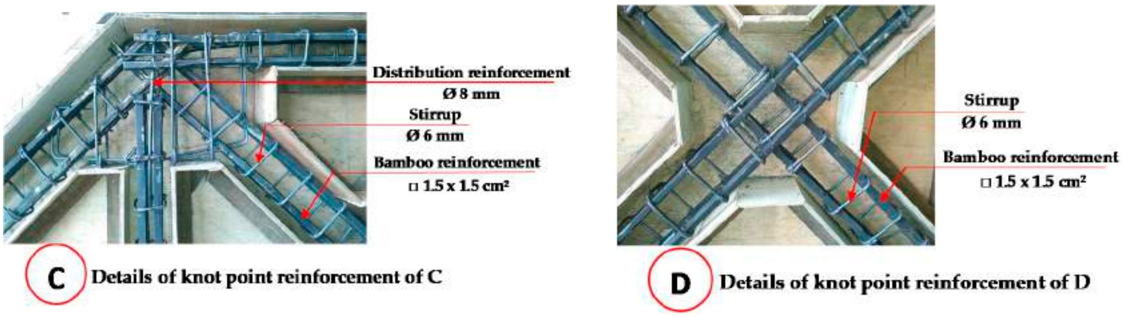
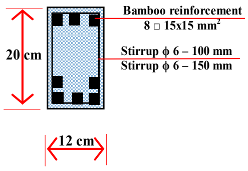
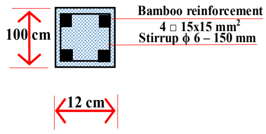
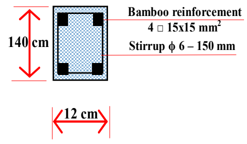


Figure 14. Details of the knot reinforcement for the bridge frames [38].

Table 4. Details of the bridge frame reinforcement [38].

Model	I (Shown in Figure 14)	II (Shown in Figure 14)	III (Shown in Figure 14)
Rigid portal model or "frame model"			

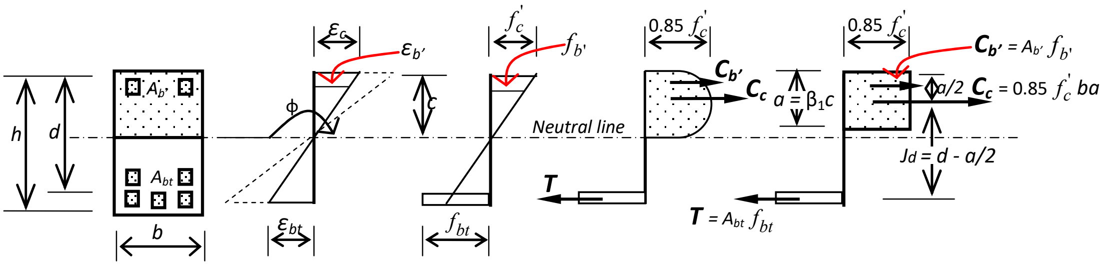


Figure 15. Stress–strain distribution diagram in a BRC beam [1,22].

Testing of the precast bridges with the bamboo reinforced concrete frames was carried out directly with a load of a minibus-type vehicle. The load was given in stages and levels, starting from a zero load, Brio carload without passengers, Brio carload full of passengers, and Avanza carload full of passengers, as shown in Figure 16. The stage of reading the response variable was carried out when the axle of the car was at the coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm, and 300 cm from the support, as shown in Figure 17. Tests were carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, four LVDTs (Linear Variable Displacement Transducers) were installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, six pieces of LVDTs were installed, two pieces of LVDTs were installed in the middle of the side frame span, and four LVDTs were installed on the side of the four ends of the beam. The performance test settings for the precast bridges of the bamboo reinforced concrete frames are described in Figure 18.

The weights of the Brio and Avanza cars were calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight was based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

Table 5. Specifications and weight of the minibus car.

Type of Car	Length	Height	Width	Wheelbase	Empty Weight or One Driver	Passenger Capacity	Weight with Full Passenger
	mm	mm	mm	mm	kg	Persons	kg
Brio	3800	1485	1680	2655	930–965	5	1280
Avanza	4190	1695	1660	2655	1045–1095	7	1550

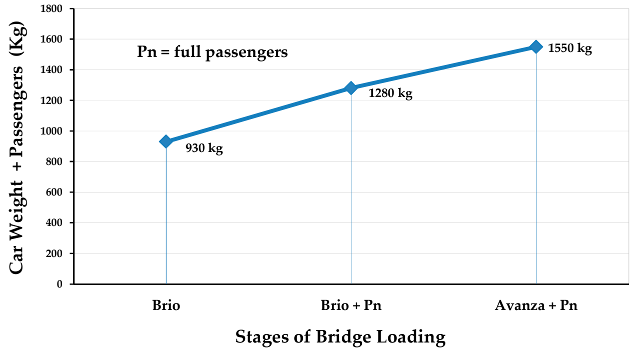


Figure 16. Loading stage of the precast bridges with a bamboo reinforced concrete frame.

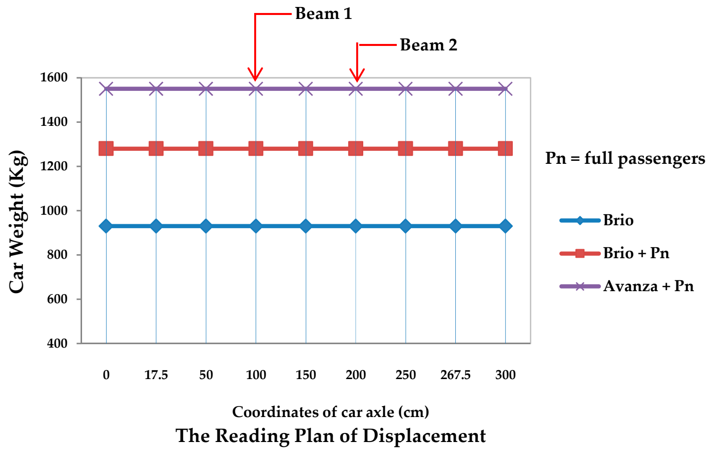


Figure 17. The coordinates of the reading points of the displacement and deformation.

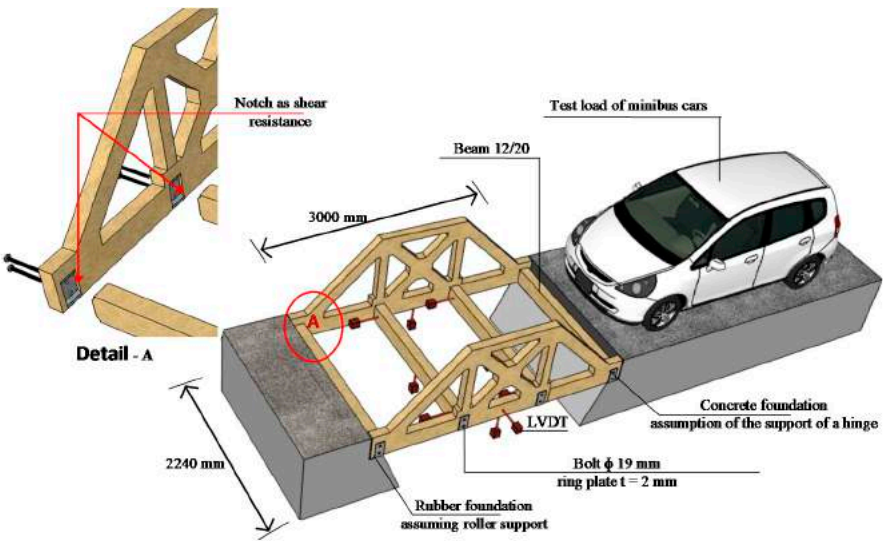


Figure 18. Arrangement of the testing of the bamboo reinforced concrete frame precast bridges.

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers, including Hidalgo (1992) in Sattar (1995) [46], Ghavami (2005) [1], Rong (2007) [47], and Lima Jr et al. (2008) [14]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [46] reported that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that, after testing, the bamboo reinforced concrete beams were left in the open air at the PUC Rio Brazil university campus; the bamboo reinforcements from the treated beams showed that the bond with the concrete was still in satisfactory condition after 15 years. Rong (2007) [47], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, stated that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement as the level of durability is good. Lima Jr et al. (2008) [14] experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength or Young's Modulus. This is an important factor in the material for use as concrete reinforcement.

2.3. The Numerical Method Used

Determining the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis was written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack was done by using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo reinforced concrete is shown in Equations (1) and (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (E). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom, as shown in Figure 19. The stress–strain relationship for the field stress problem has the form of an equation, such as Equation (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \tag{1}$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \tag{2}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{4}$$

where E is the modulus of elasticity and v is the Poisson's ratio. The principal stresses in two dimensions are calculated by Equation (4). The Fortran PowerStation 4.0 programming language for triangle elements is shown at the following link: https://bit.ly/3l1oU0d.

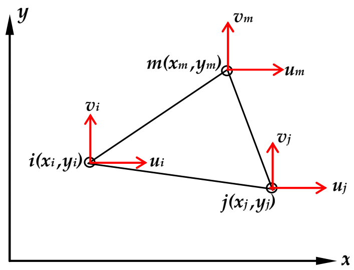


Figure 19. The degrees of freedom of the triangular element.

3. Results

Specifications for precast bridges of the bamboo reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car full of passengers. The test was carried out after several stages of work were done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, and completing or finishing the bridge. Recording of the test results started when the front axle of the minibus car was right on the hinge support and ended when the rear axle of the minibus car was right on the support of the roller. The test result data are shown in Table 7.

The security measure during the test was to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the LVDT tool. Besides, the bridge was planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test was carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and the deformation that occurred was deflection and elastic deformation. The critical load (P_{cr}) or initial crack load was 2.1 tons and the maximum test load for the minibuses was 1.55 tons.

Figures 20–25 show the beam displacement and the bridge frame with the minibus Brio car, the Brio full of passengers, and the AVANZA full of passengers. The maximum displacement with the load of the Brio car occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for the beam displacement. While, the maximum displacement with a full passenger Brio car occurred when the position of the front axle was at coordinates 200 cm and the rear axle was at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for the beam displacement. The maximum displacement with a full passenger AVANZA car load occurred when the front axle position was outside the bridge coordinates, which was 115 cm from the roller support, and the rear axle was at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for the displacement beam.

Based on the AASHTO [48] and RSNI T-12-2004 standards [49], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo reinforced concrete frame bridge meets the requirements based on the AASHTO [48] and RSNI T-12-2004 standards [49].

Table 6. Geometry and specifications of the precast bridges with a bamboo reinforced concrete frame.

Bridge span:	3 m
Foundation:	River stone
Bridge support:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam:	- Dimensions of the bridge beam 12 × 20 cm^2, tensile reinforcement (ρ) = 4.688% and compressive reinforcement ([*yellow*]ρ′) = 1.875% - Hose-clamp d = $\frac{3}{4}$ attached to the end of the bamboo reinforcement instead of hooks - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand
Connection type:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model:	Rigid portal model or "frame model"
Bridge slab:	- 10 cm thick slab + spandex t = 0.3 mm - Slab reinforcement using bamboo 1.5 × 1.5 cm^2 with a distance of 10 cm
Displacement and deformation of permit:	Based on AASHTO [48] and RSNI T-12-2004 standards [49], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge with bamboo reinforced concrete frames.

Bridge Load	Displacement and Deformation						
	Frame 1		Frame 2		Beam 1		Beam 2
	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)
Brio 930 kg	0.2	0.03	0.04	0.04	0.06	0.01	0.14
Brio + Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza + Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of the vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured as the direction of the horizontal of the cross-section.

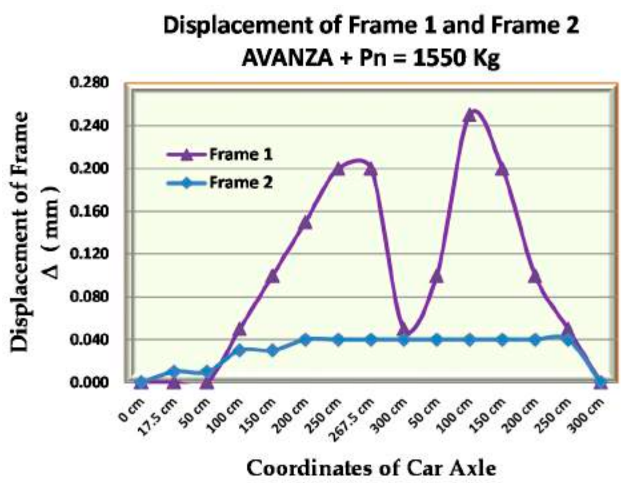


Figure 20. Displacement of the frame with loads of the Avanza car full of passengers.

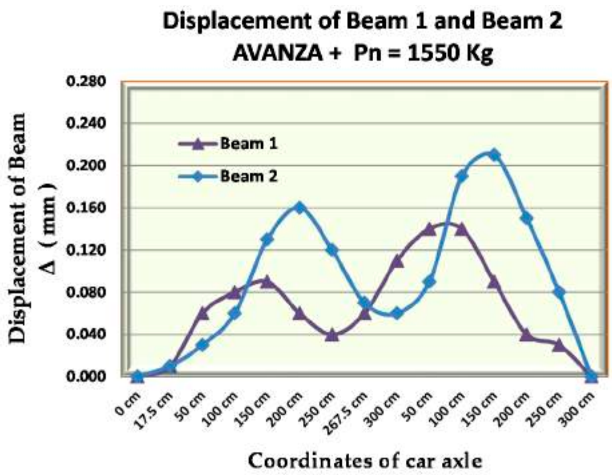


Figure 21. Displacement of the beam with loads of the Avanza car full of passengers.

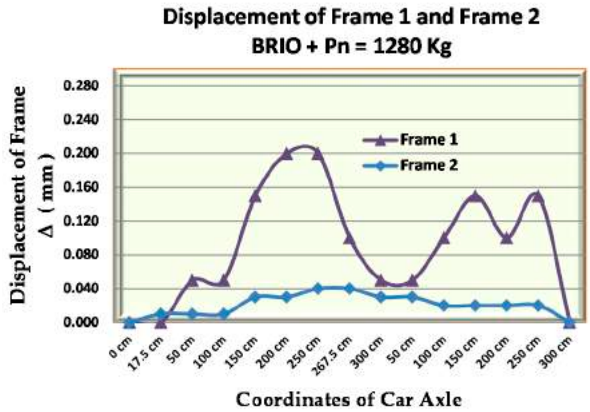


Figure 22. Displacement of the frame with loads of the BRIO car full of passengers.

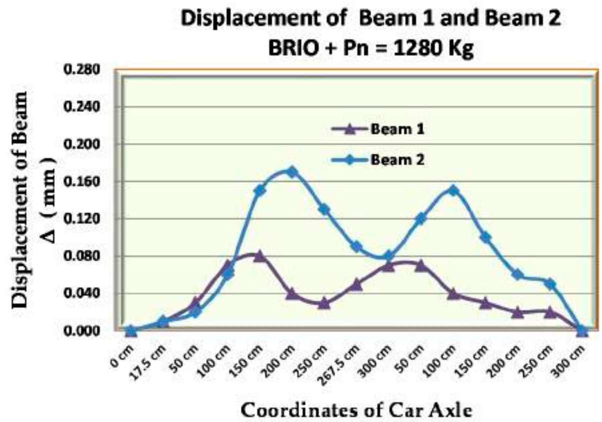


Figure 23. Displacement of the beam with loads of the BRIO car full of passengers.

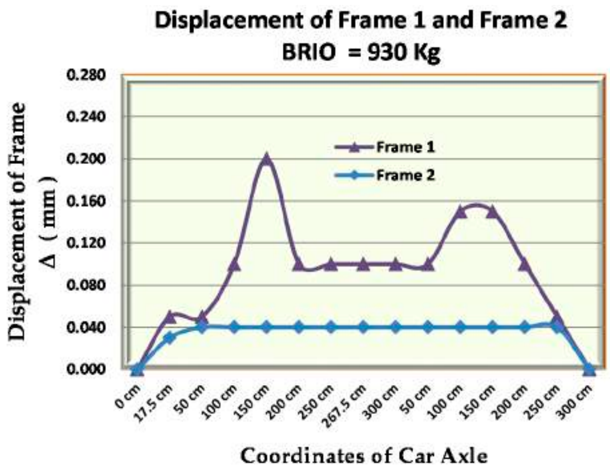


Figure 24. Displacement of the frame with loads of the BRIO car with no passengers.

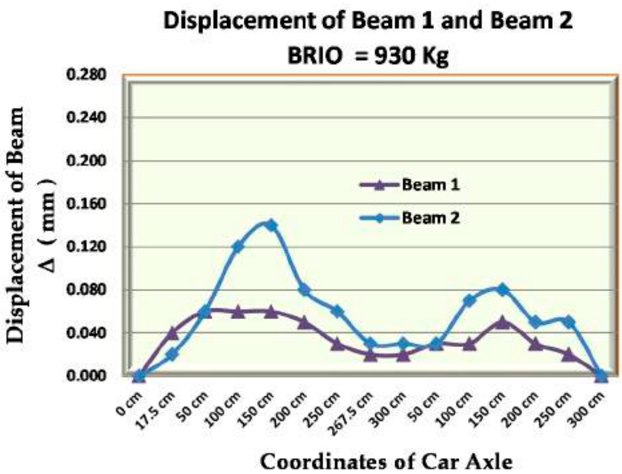


Figure 25. Displacement of the beam with loads of the BRIO car with no passengers.

Figure 26 shows the deformation of the bridge beam of the bamboo reinforced concrete with a load of Brio minibuses, the Brio car full of passengers, and the Avanza car full of passengers. From Figure 26 and Table 7, we see that the maximum deformation occurs in the beam with the load of the Avanza car with a full passenger load, which is when the position of the front axle is outside the coordinates of the bridge, which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with the deformation of the beam being 0.20 mm.

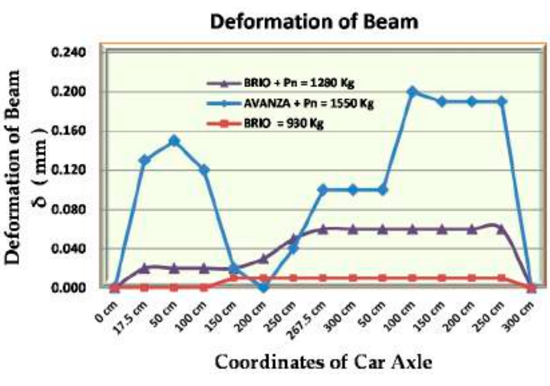


Figure 26. Deformation of the beam of the precast bridge of bamboo reinforced concrete.

Figures 27–29 show the deformation of the bridge frame with the load of the Brio minibus, Brio car full of passengers, and the Avanza car full of passengers. The maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with a frame deformation of 0.04 mm.

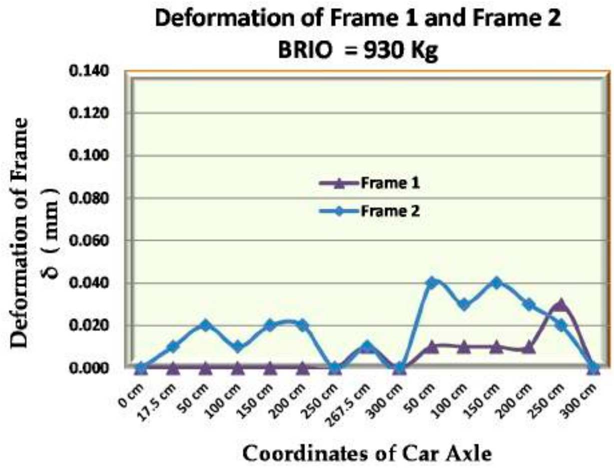


Figure 27. Deformation of the frame with loads of the Brio car with no passengers.

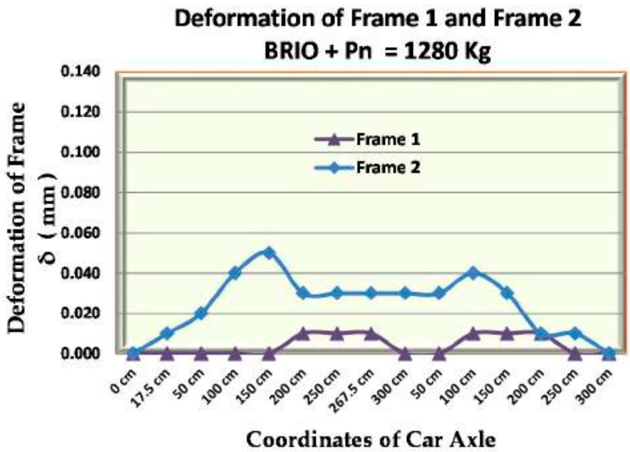


Figure 28. Deformation of the frame with loads of the Brio car full of passengers.

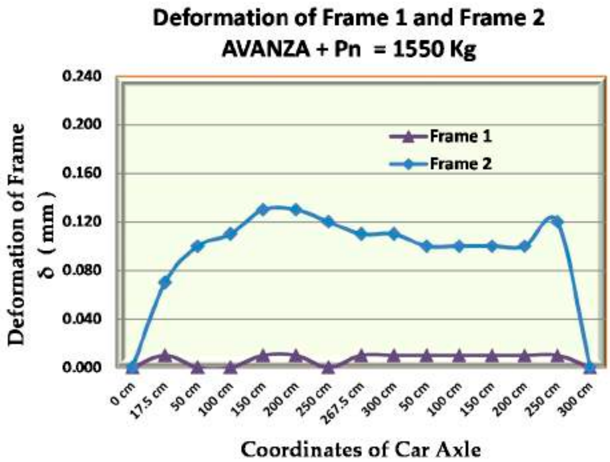


Figure 29. Deformation of the frame with loads of the Avanza car full of passengers.

The maximum frame deformation with the load of the brio car full of passengers occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the hinge support, with a deformation of 0.05 mm. The maximum deformation of the frame with the load of the Avanza car full of passengers occurred when the position of the front axle was at the coordinates of the bridge of 150 cm, and the rear axle was at a distance of 115 cm from the hinge support, with a deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to a static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured in the horizontal direction of the cross section. Measurements were made by installing LVDTs (Linear Variable Displacement Transducers) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams, as shown in Figure 30.

Figure 30. Measuring the elastic displacement and deformation.

The accuracy of the deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site, such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce the deformation and increase the deflection of the bridge beams. Figures 21 and 26 at the 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at the coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle; that is, the deformation continues to increase, respectively, at the front car axle and rear car axle. However, the accuracy of the deformation measurements needs attention as to the many determinants of accuracy that exist.

Figures 27 and 28 shows that the minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span or at the 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate; as shown in Figure 27, the coordinates at 250 cm convey inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [48] and RSNI T-12-2004 standards [49], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo reinforced concrete frame meet the requirements based on AASHTO [48] and RSNI T-12-2004 standards [49]. However, the relationship of load vs. displacement of the beam and the frame results from the field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and Surfer 9.8 software [50] based on laboratory test results. Simulations were carried out as control and validation of the experimental data. The bridge frame test simulation was carried out at the first crack load stage, which was 87 kN based on the frame loading capacity of only 100 kN. The discretization of the bamboo reinforced concrete bridge frame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figures 32 and 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [38], and with the field test results as shown in Figure 34. Figure 33 shows displacement in the X-direction; the green color shows the minimum displacement, and the orange and blue colors show the maximum positive and negative displacement, respectively. FEM analysis modeling on the bamboo reinforced concrete frames can be seen in Item 2.3 of the numerical method used.

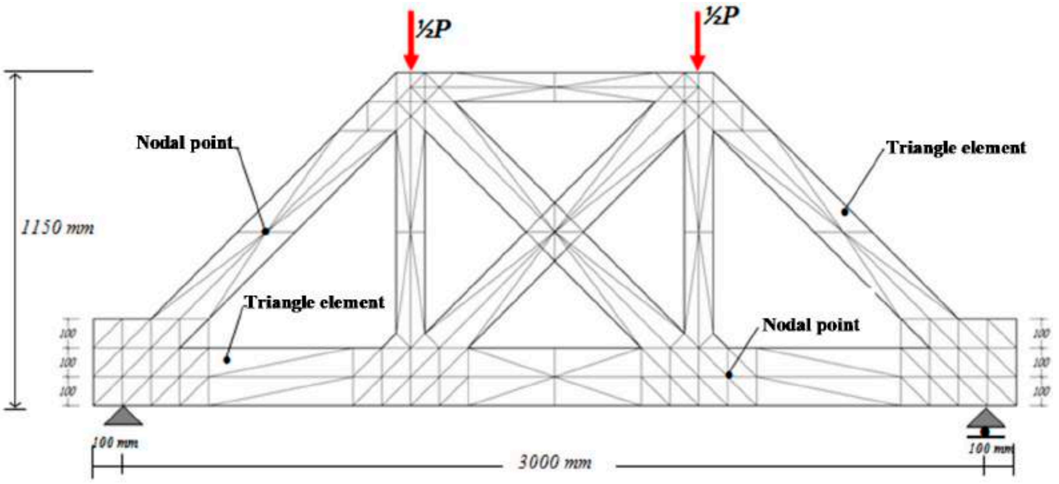


Figure 31. Discretization of the bamboo reinforced concrete bridge frames.

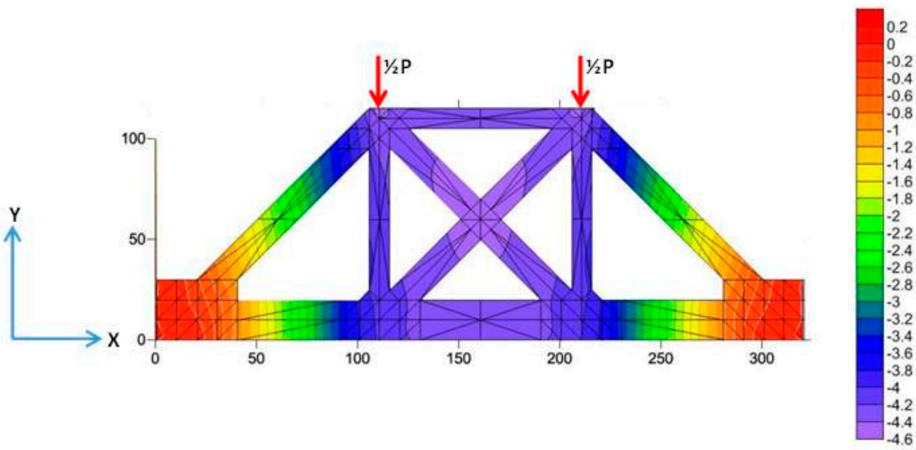


Figure 32. The displacement of Y-direction of the bridge frame.

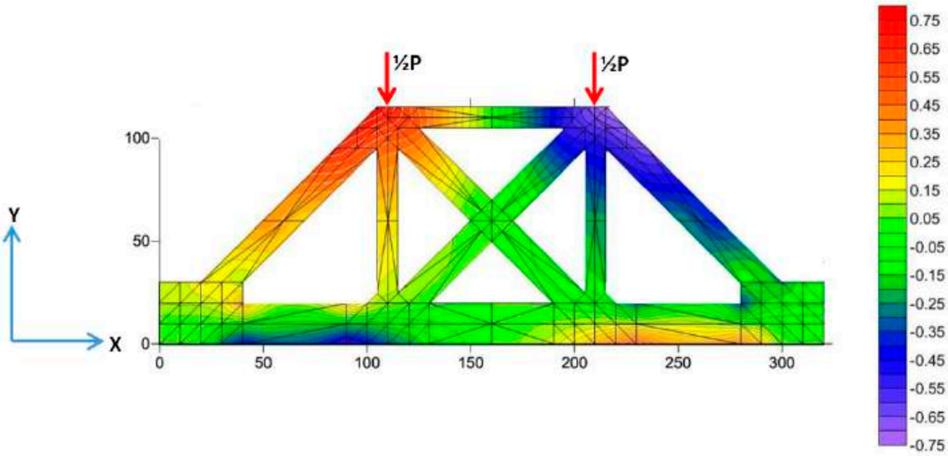


Figure 33. The displacement in the X-direction of the bridge frame.

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [24]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of the beams and bridge frames was analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [22,38], and the results of field experiments as shown in Figure 34. Control was carried out at the maximum load point of the bamboo reinforced concrete precast frame bridge test in the field, which was 15.5 kN, as shown in Figures 35 and 36. Documentation of the direct test of the bamboo reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of the aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, the SNI SNI-07-SE-2015 [51] dynamic analysis needed to be carried out for bridge types with a complex behavior, one of which was the main span exceeding 200 m. In this study, the bridge width is 2.24 m and the bridge span is 3.20 m, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements of AASHTO [48] and RSNI T-12-2004 [49], which is Δ_{max} = L/800 = 3.75 mm.

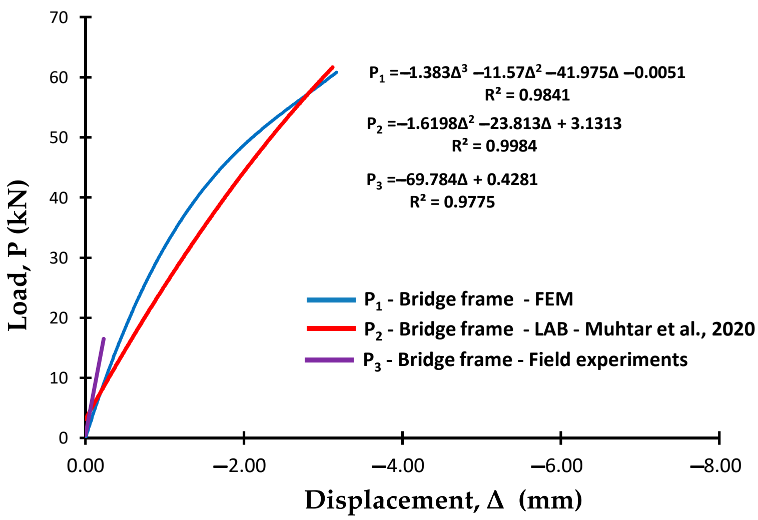


Figure 34. The relationship of load vs. displacement of the bridge frame.

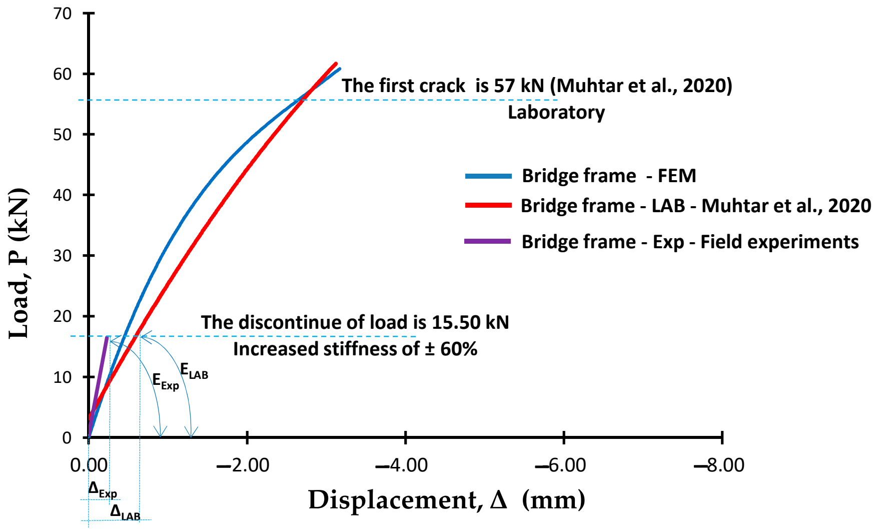


Figure 35. The relationship of load vs. displacement of the bridge frame from the laboratory test results, FEM results, and field experiment results.

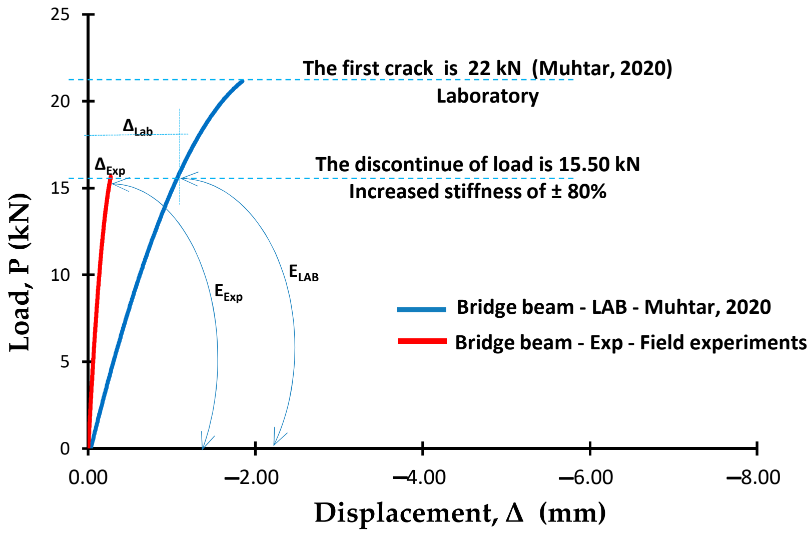


Figure 36. The relationship of load vs. displacement of the bridge beam from the laboratory test results and field experiment results.

The next step was validating the stiffness of the beam and bridge trusses. The main principle is that the bridge must be in a service condition, with a Serviceability Limit State (SLS) load. The elements of the bridge structure should not be subjected to cracks, deflection, or vibrations causing user discomfort. The allowable deflections are those that are elastic deflection and do not cause the crack. Stiffness is the main parameter of structural resistance. Therefore, the stiffness of the field test results needs to be validated by the stiffness of the laboratory test results. Load–displacement relationship diagrams of the experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results, and the displacement of the field experiments results of the bamboo reinforced concrete frame precast bridge at a stop load of 15.50 kN, the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame and 4.07 for the bridge beam. Figures 35 and 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of the laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs when the rear wheel is at the center of the span at the 150 cm coordinates and the front wheel is at the 415.5 cm coordinates (the front wheel is outside the bridge). While, the maximum displacement of the frame occurs when the rear wheel is at the 100 cm coordinates and the front wheel is at the 365.5 cm coordinates (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely, the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load of P = 15.5 kN, the stiffness of the bridge beam increased ±80% during the bridge test when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ±60% during the bridge test when compared to the frame stiffness of the laboratory results.

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Abstract

Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge were a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames were connected by four bridge beams. The bridge plate was made of a 10-cm-thick concrete plate. The bridge support of the reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus-type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm, meeting the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm. View Full-Text

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

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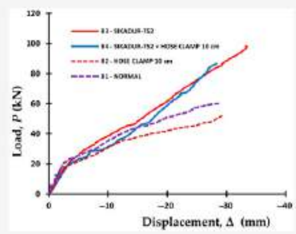

Figure 1

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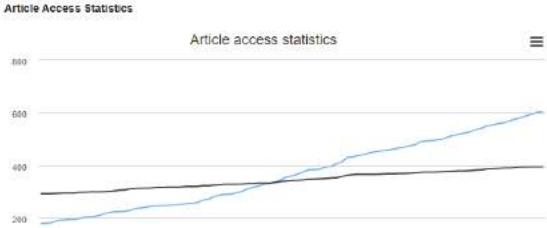

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Precast Bridges of Bamboo-~~-~~Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Received: date; Accepted: date; Published: date

Abstract: Bamboo is an inexpensive~~ building material~~, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily ~~to~~ attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo-reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge were~~are made with~~ a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames were~~are~~ connected by four bridge beams. The ~~B~~bridge plate was made of a 10-~~-~~cm-~~-~~thick concrete plate. The bridge support of the reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo-~~-~~reinforced concrete frame bridge test was carried out directly with a load of a minibus-~~-~~type vehicle. The test results show that the precast bamboo-~~-~~reinforced concrete frame bridges have sufficiently good integrity;~~,~~ that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm, meetings~~s~~ the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo-~~-~~reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [42]. Bamboo is a renewable building material, such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboo, such as tensile strength, flexural strength, and other mechanical properties, can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3–4 years [6]. ~~Also, b~~Bamboo is also very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures, such as warehouses, bridges, and village traditional houses, and for handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ±~~-~~1500 species of bamboo [2]. In terms of its potential, in 2000 the total area of bamboo plants

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in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and 1,414,000 ha of bamboo plant areas outside forest areas [27]. Arsad~~, E~~ (2015) [27] revealed that in the Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha, with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [46]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the ~~type of~~ petung bamboo (*Dendrocalamus asper*) and ~~the type of~~ ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with a high tensile strength. The use of bamboo as concrete reinforcement for simple construction ~~and~~ is applied specifically ~~to~~ in underdeveloped village areas that have a lot of bamboo.

Bamboo for concrete reinforcement is because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the tensile stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. Bamboo is suitable for use in tensile elements, simple construction, such as roof trusses, simple bridge trusses, simple house construction elements, and so on. Muhtar et al. (2018) [11] tested the pull-out of bamboo reinforcement with a layer of Sikadur®-752 and hose clamps embedded in a concrete cylinder, show~~ed~~ing an increase in tensile stress of up to 240% compared to untreated bamboo-reinforced concrete (BRC). A single ~~reinforced~~ BRC beam with a bamboo reinforcing area ratio of 4% exceeds the ultimate load of a steel-reinforced concrete (SRC) beam by 38.54% with a steel reinforcement area ratio of 0.89% [3]. However, bamboo also has weaknesses, which are being easily ~~to~~ attacked by insects and having high water absorption. This study did not test for fungal and insect attacks, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [42] and Stebbings (1904) [45], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aim to remove the starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength;~~,~~ however, after drying it undergoes a transition from a brittle behavior to a very resilient behavior [28]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [44], the content of bamboo fiber (BF)~~ which is~~ treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength. Moe Thwe (2003) [51] conducted a study on the durability of bamboo with treatment using c~~C~~alcium h~~H~~ydroxide (CaOH2) to increase flexibility and durability.

In this study, the technology used to prevent decay and absorption, and the effect of a high pH, is to provide a Sikadur adhesive that~~which~~ is also a waterproof layer, and the basis is previous research that has been conducted by several researchers, including (1) Ghavami (2005) [1], who researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel;~~,~~ (2) Agarwal et al. (2014) [5], who researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sik~~c~~adur 32 Gel. From the sticky strength test, it was found that the best adhesive was the Sik~~c~~adur 32 Gel;~~,~~ (3) Lima Jr et al. (2008) [29], who experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength or~~and~~ Young's Modulus;~~,~~ (3~~4~~) Javadian et al. (2016) [30], who did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of a high pH on the strength properties will be carried out in future studies;~~,~~ and (4~~5~~) Muhtar et al. (2019) [3], who process~~ed~~ing bamboo reinforcement by immersing in water for 1 month, coating with Sikadur®-752, and applying a hose clamp. The pull-out test results show that the bond-stress

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increases by 200% when compared to untreated bamboo. Sikadur®-752 adhesive is quite effective in preventing the occurrence of hygroscopic and hydrolysis processes between bamboo and concrete. The non-adhesive hose-clamp does not affect bond--stress.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include: (1) Ghavami (2005) [1], who concluded that bamboo can be used as a structural concrete element, including beams, windows, frames, and elements that experience bending stress;, (2) Agarwal et al. (2014) [5], who conducted tests of treated bamboo--reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements;, (3) Sakaray et al. (2012) [31], who conducted a feasibility test for the moso--type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete;, (4) Nayak et al. (2013) [32], who conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is three3 times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement;, (5) Kaware et al. (2013) [33], who reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel;, (6) Khan (2014) [34], who researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo--reinforced concrete can be used successfully for structural and non-structural elements in building construction;, (7) Rahman et al. (2011) [6], who conducted tests on bamboo--reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete;, (8) Sethia and& Baradiya (2014) [35], who in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams;, (9) Terai and& Minami (2011) [36], who conducted a study on 11 bamboo--reinforced concrete beams and tested them to check for flexural cracks and shear cracks, . Aand concluded that the crack pattern of bamboo--reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo-reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel--reinforced concrete beams;, and (10) Muhtar (2020) [12], who conducted a flexural test on 4four beams with untreated bamboo reinforcement and treated with Sikadur®-752 and a hose--clamp. The test results showed that the beam treated with Sikadur®-752 increased the load capacity by 164% when compared to the untreated reinforced bamboo. With the first treatment, bamboo is suitable for use as a simple construction concrete reinforcement.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [3-4], drying in free air [5,6], applying a waterproof layer [7], and sprinkled with sand, to modify the roughness of the bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [8], Sikadur 32 Gel [1,5], and Sikadur®-752 [4,7,9–12]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond -stress of bamboo reinforcement [4]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [13–16], bamboo as column reinforcement [17–19], bamboo as slab reinforcement, or panels reinforcement [20–22], and bamboo as a bridge frame reinforcement [23,24].

Muhtar [12] tested the flexural properties of four4 types of bridge beams with different treatments. The size of the bridge beam is 120 mm × 200 mm × 2100 mm with the area of tensile reinforcement ϱ = 4.68% and compressive reinforcement ϱ′ = 1.88%. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose -clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of the bamboo reinforcement with adhesive, sand, and hose -clamp can increase the bond -stress and capacity of the bamboo--reinforced concrete beam (BRC beam) [12]. The relationship between load vs. displacement is shown in Figure 1.

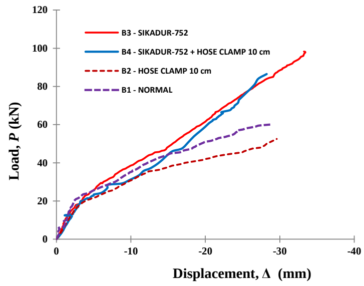

Figure 1. The relationship of l~~L~~oad vs. deflection of the bamboo-reinforced concrete (BRC) beam [12].

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Testing of bridge trusses has been carried out by several researchers, including bamboo as reinforcement for a truss easel [24] and as reinforcement for a bridge frame with a span of 3 m [23]. Dewi and Wonlele [24] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of the support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength;~~,~~ however, the collapse pattern still shows a bending effect [24].

Muhtar et al. [23] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", and one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has a higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of the load (*P*) vs. deflection (*Δ*) of the two bridge frames is shown in Figure 2.

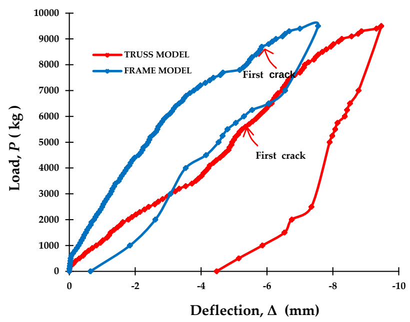

Figure 2. The relationship pattern of load vs. deflection of the bridge frame [23].

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The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [12]. In this study, strengthening of the reinforcement with hose~~-~~ clamps is only for~~to~~ tensile reinforcement, whereas in previous studies it was carried out for~~on~~ all reinforcements. H~~The h~~ose-clamp~~s~~ strengthening when~~ith~~ the distance is too close~~tightly~~ together can reduce the elastic properties of the bamboo and reduce its capacity. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [23]. The reinforcement model on the lower side frame stem is installed with the concept of flexural reinforcement, whereas in previous studies it was carried out with the concept of truss reinforcement or symmetry, and their behavior shows flexural behavior. The basis for using the results of previous laboratory research is to control the results of the direct tests in the field. The novelty that is expected is~~:~~ (1) obtaining a prototype of the precast concrete reinforced concrete bridge,~~;~~ and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. ~~While t~~The expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement, which could be~~is~~ applied to a simple frame bridge structure in underdeveloped village areas with local materials that are~~,~~ cheap, environmentally friendly, and acceptable.

The targets to apply ~~of~~ this research to~~application~~ are underdeveloped villages with~~and~~ lots of bamboos. Bamboo is a new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including for reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used ~~is~~ was the petung bamboo (*Dendrocalamus asper*), aged 3–5 years [4,5]. For the ~~P~~petung bamboo, the bamboo shoots are purplish-black, covered with hairs that are~~such as~~ velvety brown~~ velvet~~ to blackish. Petung bamboo is large, with a segment length 40–50 cm, diameter 12–18 cm, and~~with~~ a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, as per Brink ~~M~~ (2008) in Wikipedia Indonesia (2016) [42]. The mechanical properties of petung bamboo are shown in Table 1. The tensile test for bamboo petung was based on ASTM D 143-94 [37].

Table 1. Mechanical properties of petung bamboo [47].

Mechanical Properties	
Tensile strength (MPa)	105 ± 8
Modulus of elasticity (GPa)	26 ± 5
Elongation of fault (%)	16 ± 1
Flexural strength (MPa)	153 ± 11
Hardness (VHN)	5 ± 1
Impact strength (J/mm^2)	0.15 ± 0.7

The bamboo part that is taken ~~is~~was 6–7 m from the base of the bamboo stem. The b~~B~~amboo was~~is~~ cut and split into a bamboo reinforcement size ~~with a size~~ of 15 × 15 mm^2. The b~~B~~amboo to be used must be treated with the following steps: (a) the bamboo must be~~is~~ cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm × 15 mm × 2000 mm for bridge beam reinforcement, and 15 mm × 15 mm × 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm × 15 mm × 1100 mm, the top stem is 15 mm × 15 mm × 1100 mm, and the diagonal stem is 15 mm × 15 mm × 1300 mm;~~,~~ (b) the bamboo must be~~is~~ soaked in water for 1–2 months to remove the sugar content and prevent termites and insects, as shown in Figure 3 [45];~~,~~ (c) it should be dried~~y~~ in free air until the moisture content is approximately 12%, as shown in Figure 4;~~,~~ (d) the bamboo reinforcement should be~~is~~ trimmed with a grinding machine according to the specified size, as shown in Figure 5;~~,~~ (e) one should provide~~ing~~ a waterproof layer to reduce the occurrence of the hydrolysis process between the bamboo and concrete, as shown in Figure 6;~~,~~ (f) do sand sprinkling to modify the roughness of the bamboo reinforcement, as shown in Figure 7;~~,~~ and (g) ~~S~~stringing the bamboo reinforcement, as shown in Figure 8.

Ghavami (2005) [1] and Agarwal et al. (2014) [5] concluded that the best waterproof layer is Sikadur 32 Gel. Muhtar (2019) [3] treated bamboo with Sikadur®-752 and a hose~~-~~ clamp. The test results show that the adhesion strength increases up to 200% and the beam capacity increases 164% when compared to untreated bamboo reinforcement. The waterproof or adhesive layer used here~~s~~ was Sikadur®-752, produced by PT Sika Indonesia [3,10]. Sikadur®-752 is ~~A~~a solvent-free, two~~2~~-component, super-low viscosity -liquid, based on high strength epoxy resins~~.~~ — ~~E~~especially for injecting into the cavities and cracks in concrete. Usually used to fill and seal cavities and cracks in structural concrete,. Sikadur®-752 is applied to the bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage. The thermal effect of Sikadur®-752 on bamboo reinforcement can be prevented by the moisture content of 12% in bamboo. In determining the strength of the bamboo, a 12% of moisture content in the air-dry condition has been considered as a reference standard [48], and the temperature does not significantly affect the loss of stiffness [49]. Chemical treatment of bamboo helps increase the durability of the bamboo fibers and reduces the moisture absorption of the bamboo fibers [50].

Table 2. The specifications of Sikadur®-752 [41].

Components	Properties
Colouur	Yellowish
Density	Approx. 1.08 kg/L
Mixing Ratio, by weight/volume	2:1
Pot life at +30 °C	35 min
Compressive strength	62 N/mm² at 7 days (ASTM D-695) 64 N/mm² at 28 days
Tensile strength	40 N/mm² at 28 days (ASTM D-790)
Tensile aAdhesion Sstrength	2 N/mm² (Concrete failure, over mechanically prepared concrete surface)
Coefficient of Tthermal eExpansion	−20 °C to +40 °C,– 89 × 10⁻⁶ per °C
Modulus of elasticity	1060 N/mm²

The hose- clamp used had a is diameter of ¾", made in Taiwan [3,12]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm in diameter, with a f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of the bamboo (E_b) was 17,236 MPa, with a tensile strength of 127 N/mm² [3], and the modulus of steel elasticity (E_s) was 207,736 MPa [3]. The concrete mixture used wasis Portland Pozzolana Cement (PPC), with a pH of 7, as well as sand, coarse aggregate, and water with a mixed proportion of 1.81:2.82:0.52, as shown in Table 3. The average compressive strength of the concrete wasis 31.31 MPa at the age of 28 days. The process of treating the bamboo to assembling the bamboo reinforcement can be seen in Figures 3–8.

Table 3. The mix composition of the concrete.

The Cconcrete Mix Design	Cement (PPC)	Fine Aggregate	Coarse Aggregate	Water
	Kg/m³			
Material per -m³	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

Figure 3. Take bamboo from the soaking.

Figure 4. Drying bamboo in free air.

Figure 5. Tidy up the bamboo according to size.

Figure 6. Gives a waterproof coating.

Figure 7. Sand sprinkling on bamboo reinforcement.

Figure 8. Stringing the bamboo reinforcement.

2.2. Methods

The dimensions of the bridge ~~are~~ were~~made with~~ a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge was~~is made~~ 280 cm. Two bridge frames were~~are~~ connected by four bridge beams. Each end of the bridge beam was~~is~~ connected to the knot point with ~~2~~two bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of the joints between the beam and precast bridge frame are shown in Figures 10 and 11. The bridge supports were~~are~~ made of reinforced concrete with the assumption of hinge

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support and a rubber bearing assuming roller support. T~~While t~~he bridge plate was~~is made of~~ a 10-cm-thick concrete plate with 0.3-mm-thick spandex. The shape and model of the precast bridge of the bamboo-reinforced concrete frame are described in Figure 12. Details of the reinforcement of the precast bridge beams are shown in Figure 13. Details of the reinforcement of the bridge frame are shown in Figures 14 and 15 and Table 4.

The design concept of the bamboo-reinforced concrete beams follows Ghavami (2005) [1] and Muhtar (2020) [12], as shown in Figure 9. The balance of the concrete compressive force (C = Cb ′+ Cc) and the tensile force (T) must be met, as shown in Figure 9. The tensile strength of the bamboo reinforcement (T) was~~is~~ obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo-reinforced concrete beams was due to the breaking of the bonds between the bamboo and concrete.

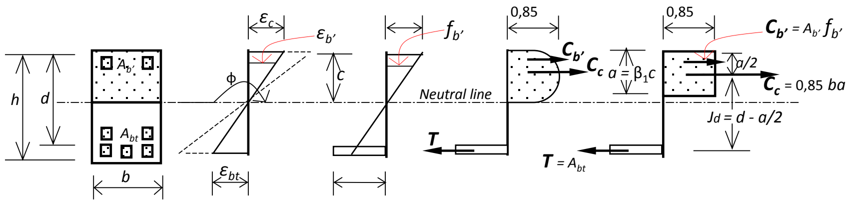

Figure 9. Stress–strain distribution diagram in a BRC beam [1,12].

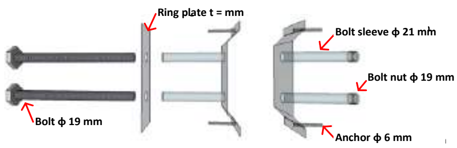

Figure 10. Details of the ring plate and bolt sleeve.

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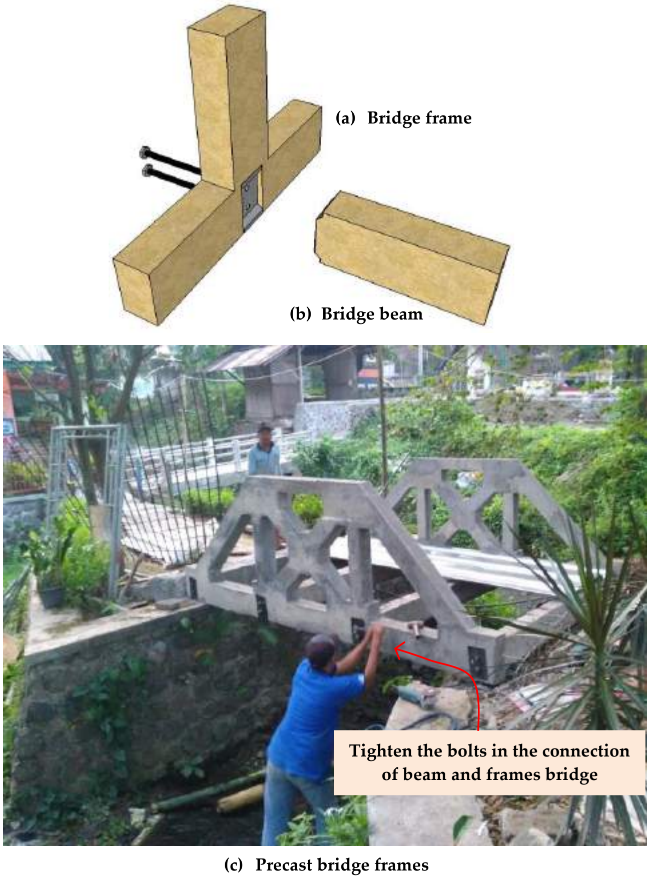

Figure 11. Models and applications of the precast connections.

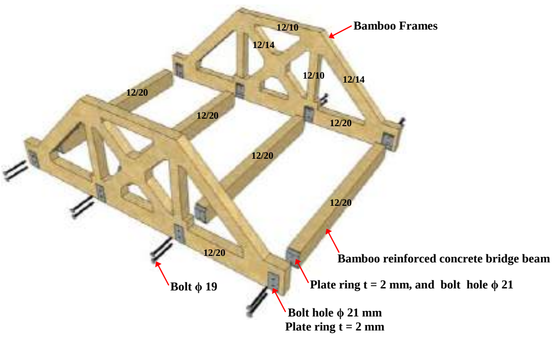

Figure 12. Model of the precast bridge made from bamboo-reinforced concrete.

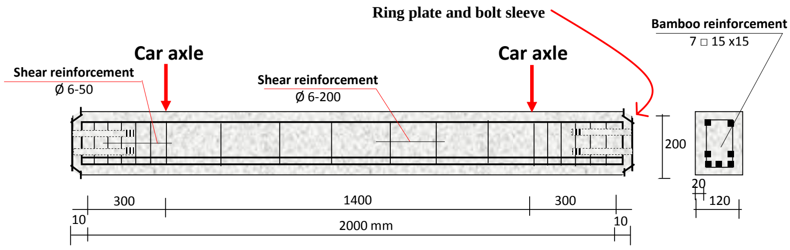

Figure 13. Details of the pPrecast bridge beam reinforcement [12].

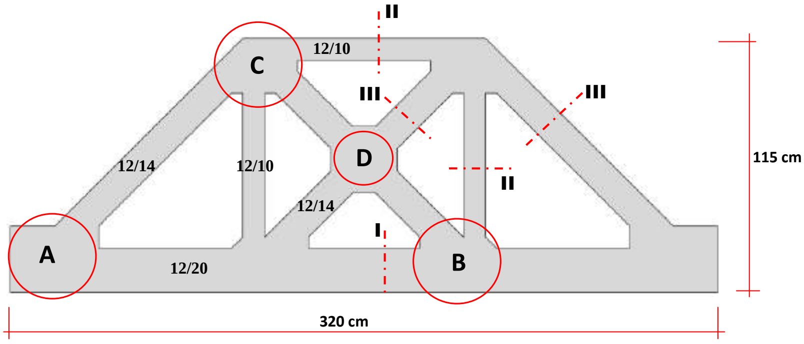

Figure 14. Details of the precast bridge frame [23].

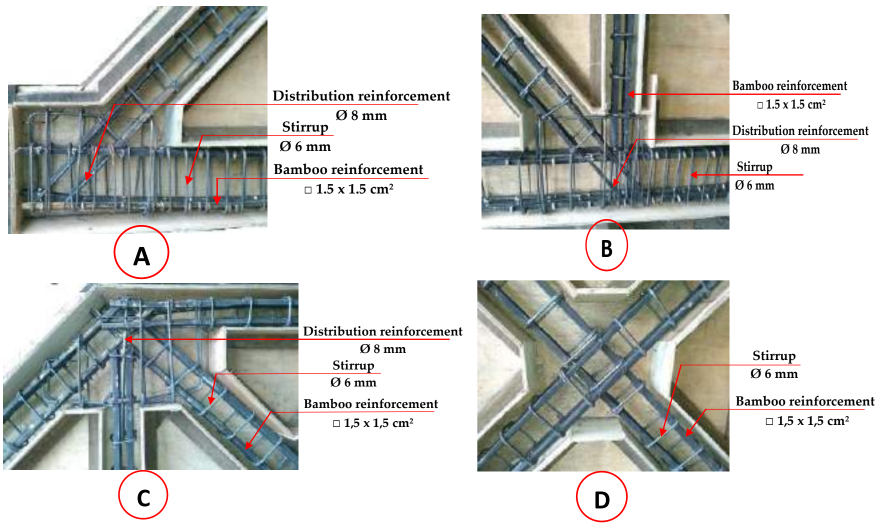

Figure 15. Details of the knot reinforcement for the bridge frames [23].

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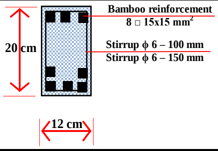
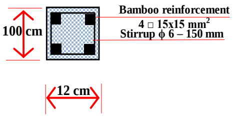
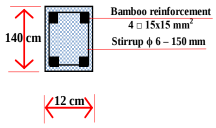
Table 4. Details of the bridge frame reinforcement [23].

Model	I (Shown in Figure 14)	II (Shown in Figure 14)	III (Shown in Figure 14)
Rigid portal model or "frame model"			

Testing of the precast bridges with the bamboo-~~-~~reinforced concrete frames was~~is~~ carried out directly with a load of a minibus-~~-~~type vehicle. The load was~~is~~ given in stages and levels, starting from a zero load~~s~~, Brio carload without passengers, Brio carload ~~of~~ full of passengers, and Avanza~~VANZA~~ carload ~~of the~~ full of passengers, as shown in Figure 16. The stage of reading the response variable was~~is~~ carried out when the axle of the car was~~is~~ at the coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm, and 300 cm from the support, as shown in Figure 17. Tests ~~are~~ were carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, four~~4~~ LVDTs (Linear Variable Displacement Transducers) were~~are~~ installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, six~~6~~ pieces of LVDTs were installed, ~~2~~two pieces of LVDTs were installed in the middle of the side frame span, and four~~4~~ LVDTs were installed on the side of the four ends of the beam. The performance test settings for the precast bridges of the bamboo-reinforced concrete frames are described in Figure 18.

The weights of the Brio ~~car~~ and ~~the~~ Avanza cars were ~~is~~ calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight was~~is~~ based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

Table 5. Specifications and weight of the minibus car.

Type of Car	Length	Height	Width	Wheelbase	Empty Weight or One Driver	Passenger Capacity	Weight with Full Passenger
	mm	**mm**	**mm**	**mm**	**kg**	**persons**	**kg**
Brio	3800	1485	1680	2655	930–965	5	1280
Avanza	4190	1695	1660	2655	1045–1095	7	1550

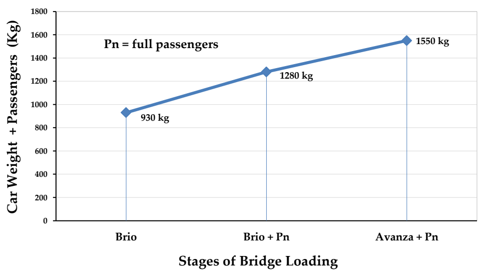


Figure 16. Loading stage of the precast bridges ~~of~~ with a bamboo-reinforced concrete frame.

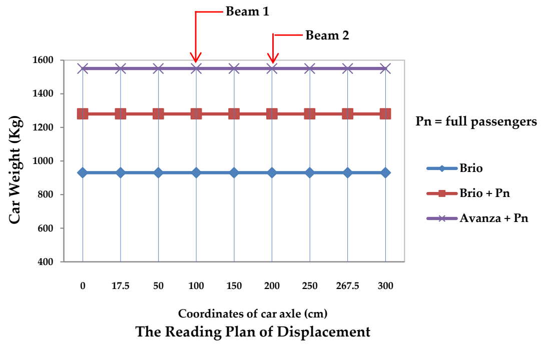


Figure 17. The coordinates of the reading points of the displacement and deformation.

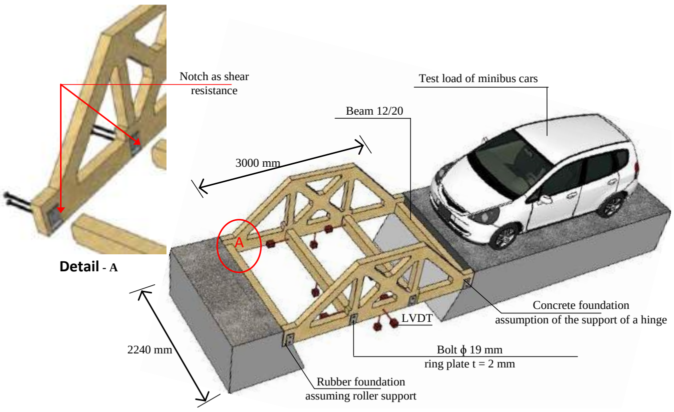


Figure 18. Arrangement of the testing of the~~for~~ bamboo-reinforced concrete frame precast bridges.

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers, including Hidalgo (1992) in Sattar (1995) [43], Ghavami (2005) [1], Rong ~~BS~~ (2007) [40], and Lima Jr et al. (2008) [29]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [43] reported~~s~~ that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that, after testing, the bamboo-reinforced concrete beams were~~are~~ left in the open air at the PUC Rio Braz~~s~~il university campus; the~~,~~ bamboo reinforcements from the treated beams showed that the bond with the concrete was~~is~~ still in satisfactory condition after 15 years. ~~B.S.~~ Rong (2007) [40], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, stated~~s~~ that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement as~~with~~ the level of durability is good. Lima Jr et al. (2008) [29] experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength ~~and~~or Young's Modulus. This is an important factor in the material for use as concrete reinforcement.

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2.3. *The Numerical Method Used*

D~~To d~~etermininge~~e~~ the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis was~~is~~ written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack was done by using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo-~~-~~reinforced concrete is shown in Equations (1) and (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (*E*). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom, as shown in Figure 19. The stress–~~-~~strain relationship for the field stress problem has the form of an equation, such as Equation (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \tag{1}$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \tag{2}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{4}$$

where *E* is the modulus of elasticity and *ν* is the Poisson's ratio. ~~And t~~The principal stresses in two dimensions are calculated by Equation (4). The Fortran PowerStation 4.0 programming language for triangle elements is shown at the following link: https://bit.ly/3l1oU0d.

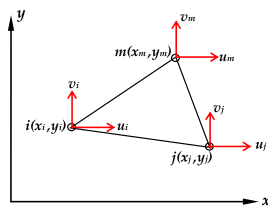

Figure 19. The degrees of freedom of the triangular element.

3. Results

Specifications for precast bridges of the bamboo-~~-~~reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car ~~of the~~ full of passengers. The test was~~is~~ carried out after several stages of work were~~are~~ done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, and completing or finishing the bridge. Recording of the test results ~~response~~ started~~s~~ when the front axle of the minibus car ~~is~~ was right on the hinge support and ended~~s~~ when~~until~~ the rear axle of the minibus car was~~is~~ right on the support of the roller. The test result data are~~is~~ shown in Table 7.

The security measure during the test iswas to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the LVDT tool. Besides, the bridge wasis planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test wasis carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and the deformation that occurreds wasis deflection and elastic deformation. The critical load (Pcr) or initial crack load wasis 2.1 tons and the maximum test load for the minibusses wasis 1.55 tons.

Figures 20–25 show the beam displacement and the bridge frame with the minibus Brio car, the Brio with full of passengers, and the AVANZA with full of passengers. The maximum displacement with the load of the Brio car occurreds when the position of the front axle wasis at coordinates 150 cm and the rear axle wasis at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for the beam displacement. While, the maximum displacement with a full passenger Brio car occurreds when the position of the front axle wasis at coordinates 200 cm and the rear axle is was at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for the beam displacement. For The maximum displacement with a full passenger AVANZA car load occurreds when the front axle position wasis outside the bridge coordinates, which wasis 115 cm from the roller support, and the rear axle wasis at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for the displacement beam.

Based on the AASHTO [38] and RSNI T-12-2004 standards [25], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo--reinforced concrete frame bridge meets the requirements based on the AASHTO [38] and RSNI T-12-2004 standards [25].

Table 6. Geometry and specifications of the precast bridges with a bamboo--reinforced concrete frame.

Bridge span:	3 m
Foundation:	River stone
Bridge support:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam:	- Dimensions of the bridge beam 12 × 20 cm², tensile reinforcement (ϱ) = 4.688% and compressive reinforcement (ϱ') = 1.875% - Hose-clamp d = ¾ attached to the end of the bamboo reinforcement instead of hooks. - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand
Connection type:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model:	Rigid portal model or "frame model"
Bridge slab:	- 10 cm thick slab + spandex t = 0.3 mm. - Slab reinforcement using bamboo 1.5 × 1.5 cm² with a distance of 10 cm
Displacement and deformation of permit:	Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge with of bamboo--reinforced concrete frames.

Bridge Load	**Displacement and Deformation**						
	Frame 1		**Frame 2**		**Beam 1**		**Beam 2**
	Displacement [1] (mm)	**Deformation [2] (mm)**	**Displacement [1] (mm)**	**Deformation [2] (mm)**	**Displacement [1] (mm)**	**Deformation [2] (mm)**	**Displacement [1] (mm)**
Brio	0.2	0.03	0.04	0.04	0.06	0.01	0.14

930 kg							
Brio + Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza + Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of the vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured asin the direction of the horizontal of the cross-section.

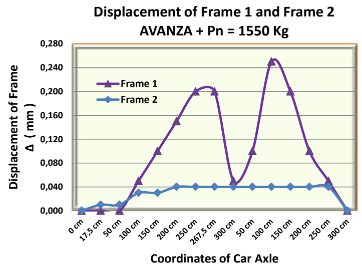

Figure 20. Displacement of the frame with loads of the AvanzaVANZA car of full of passengers.

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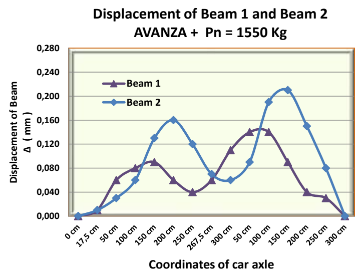

Figure 21. Displacement of the beam with loads of the AvanzaVANZA car of full of passengers.

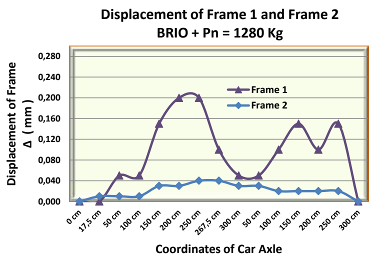

Figure 22. Displacement of the frame with loads of the BRIO car of full of passengers.

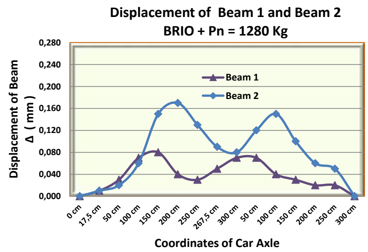

Figure 23. Displacement of the beam with loads of the BRIO car ~~of~~ full of passengers.

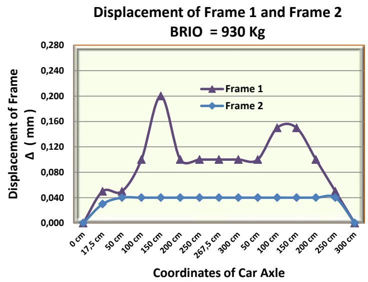

Figure 24. Displacement of the frame with loads of the BRIO car ~~of~~ with no passengers.

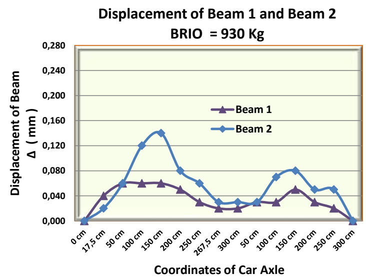

Figure 25. Displacement of the beam with loads of the BRIO car ~~of~~ with no passengers.

Figure 26 shows the deformation of the bridge beam of the bamboo-reinforced concrete with a load of Brio minibus~~s~~es~~ car~~, the Brio car ~~with~~ full of passengers, and the Avanza~~VANZA~~ car ~~with~~ full of passengers. From Figure 26 and Table 7, we see~~it shows~~ that the maximum deformation occurs in the beam with the load of the Avanza~~VANZA~~ car with a full passenger load, which is when the position of the front axle is outside the coordinates of the bridge, which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with the deformation of the ~~a~~ beam ~~of~~ being 0.20 mm.

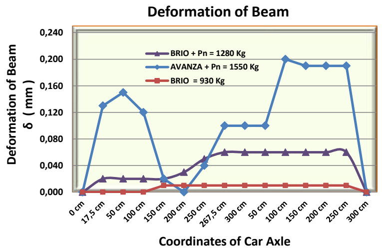

Figure 26. Deformation of the beam of the precast bridge of bamboo-reinforced concrete.

Figures 27–29 show ~~that~~ the deformation of the bridge frame with the load of the Brio minibus, Brio car ~~with~~ full of passengers, and the Avanza~~VANZA~~ car ~~with~~ full of passengers. The ~~M~~maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with a frame deformation of 0.04 mm.

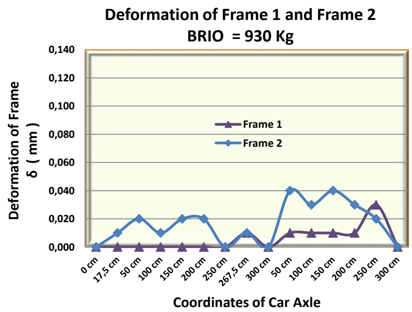

Figure 27. Deformation of the frame with loads of the Brio~~RIO~~ car with~~of~~ no passengers.

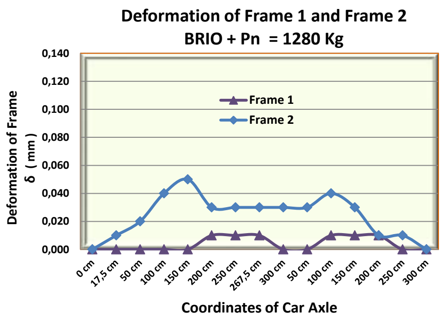

Figure 28. Deformation of the frame with loads of the Brio~~RIO~~ car ~~of~~ full of passengers.

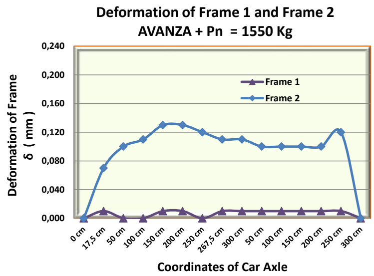

Figure 29. Deformation of the frame with loads of the Avanza~~VANZA~~ car ~~of~~ full of passengers.

T~~While t~~he maximum frame deformation with the load of the brio car ~~with~~ full of passengers occurred~~s~~ when the position of the front axle was~~is~~ at coordinates 150 cm and the rear axle was~~is~~ at a distance of 85 cm from the hinge support, with a deformation of 0.05 mm. ~~For t~~The maximum deformation of the frame with the load of the Avanza~~VANZA~~ car ~~with~~ full of passengers occurred~~s~~ when the position of the front axle was~~is~~ at the coordinates of the bridge ~~is~~of 150 cm, and the rear axle was~~is~~ at a distance of 115 cm from the hinge support, with a deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to a static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured in the horizontal direction of the cross-section. Measurements were made by installing LVDTs (Linear Variable Displacement Transducers) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams, as shown in Figure 30.

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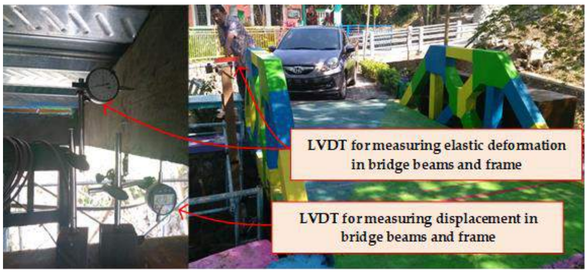

Figure 30. M~~The m~~easuring the elastic displacement and deformation.

The accuracy of the deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site, such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam;~~,~~ this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce the deformation and increase the deflection of the bridge beams. Figures 21 and 26 at the 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at the coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle;~~,~~ that is, the deformation continues to increase, respectively, at~~of~~ the front car axle and rear car axle. However, the accuracy of the deformation measurements needs attention as to the many determinants of accuracy that exist.

Figures 27 and 28 shows that the minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span or at the 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate;, as shown in Figure 27, the coordinates atof 250 cm conveyoccur inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [38] and RSNI T-12-2004 standards [25], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo-reinforced concrete frame meet the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25]. However, the relationship of load vs. displacement of the beam and the frame results from the field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and Ssurfer 9.8 software [26] based on laboratory test results. Simulations were carried out as control and validation of the experimental data. The bridge frame test simulation wasis carried out at the first crack load stage, which wasis 87 kN based on the frame loading capacity of only 100 kN. The discretization of the bBamboo- Rreinforced cConcrete bBridge fFrame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figures 32 and 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [23], and with the field test results as shown in Figure 34. Figure 33 shows displacement in the Xx-direction;, the green color shows the minimum displacement, and the orange, and blue colors shows the maximum positive and negative displacement, respectively. FEM analysis modeling on the bamboo-reinforced concrete frames can be seen in Iitem 2.3 of the numerical method used.

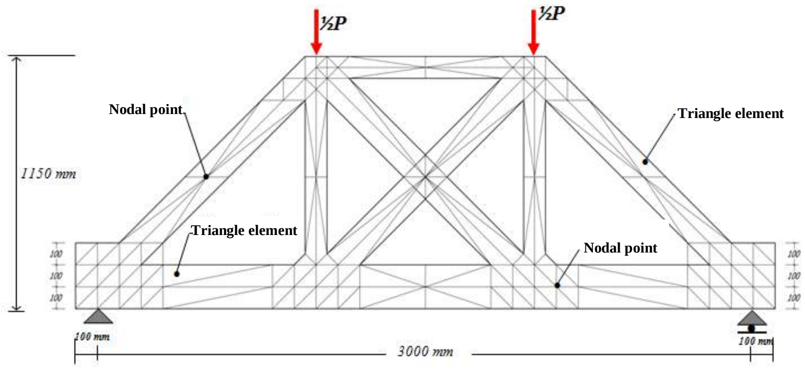

Figure 31. Discretization of the bamboo-reinforced concrete bridge frames.

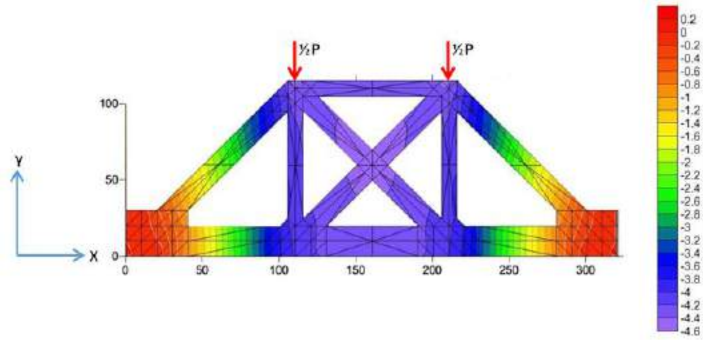

Figure 32. The displacement of Y-direction of the bridge frame.

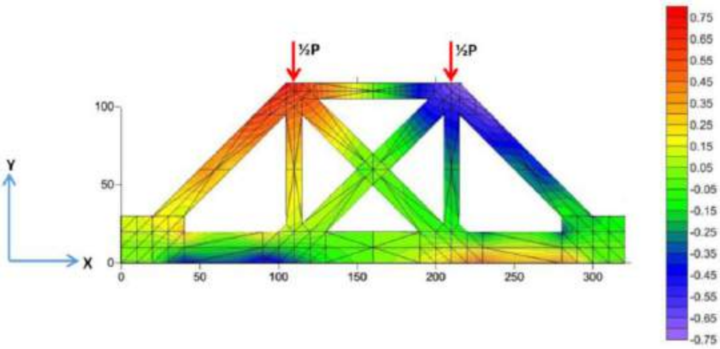

Figure 33. The displacement in theof X-direction of the bridge frame.

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [7]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of the beams and bridge frames wasis analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [12,23], and the results of field experiments as shown in Figure 34. Control wasis carried out at the maximum load point of the bamboo--reinforced concrete precast frame bridge test in the field, which wasis 15.5 kN, as shown in Figures 35 and 36. Documentation of the direct test of the bamboo--reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of the aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, the SNI SNI-07-SE-2015 [39] dynamic analysis neededs to be carried out for bridge types with a complex behavior, one of which wasis the main span exceeding 200 m. In this study, the bridge width is 2.24 m and the bridge span is 3.20 m, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements of. AASHTO [38] and RSNI T-12-2004 [25], which that is Δ_{max} = L/800 = 3.75 mm.

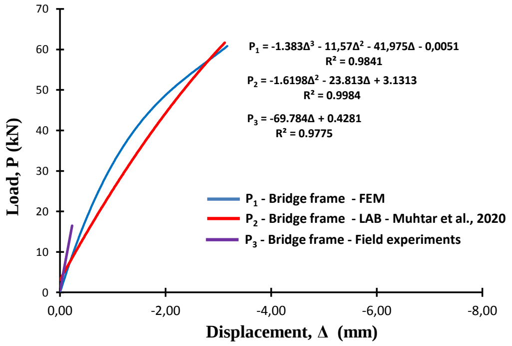

Figure 34. The relationship of load vs. displacement of the bridge frame.

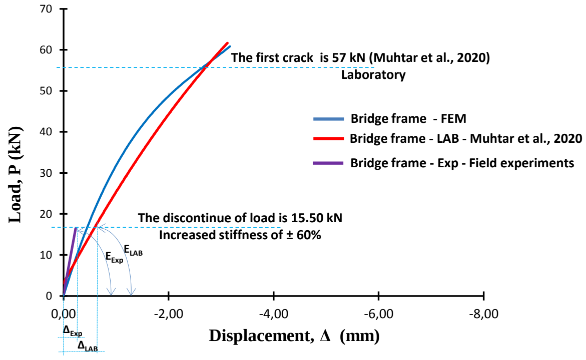

Figure 35. The relationship of load vs. displacement of the bridge frame from the laboratory test results, FEM results, and field experiment results.

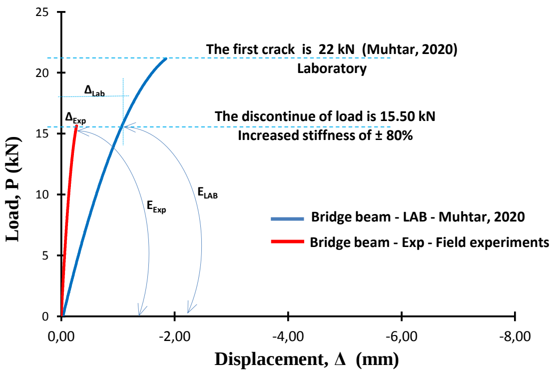

Figure 36. The relationship of load vs. displacement of the bridge beam from the laboratory test results and field experiment results.

The next step was~~is~~ validating the stiffness of the beam and bridge trusses. The main principle is that the bridge must be in a service condition, with a Serviceability Limit State (SLS) load. The elements of the bridge structure should not be subjected to cracks, deflection, or vibrations causing user discomfort. The allowable deflections are those that are elastic deflection and do not cause the crack. Stiffness is the main parameter of structural resistance. Therefore, the stiffness of the field test results needs to be validated by the stiffness of the laboratory test results. Load–displacement relationship diagrams of the experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results, and the displacement of the field experiments results of the bamboo-reinforced concrete frame precast bridge at a stop load of 15.50 kN, ~~obtained~~ the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame and 4.07 for the bridge beam. Figures 35 and 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of the laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs when the rear wheel is at the center of the span at the~~of~~ 150 cm coordinates and the front wheel is at the 415.5 cm coordinates (the front wheel is outside the bridge). While, the maximum displacement of the frame occurs when the rear wheel is at the ~~coordinates~~ 100 cm coordinates and the front wheel is at the ~~coordinates~~ 365.5 cm coordinates (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely, the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo-reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load of P = 15.5 kN, the stiffness of the bridge beam increased ±80% during the bridge test when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ±60% during the bridge test when compared to the frame stiffness of the laboratory results.

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Conflicts of Interest: The author declares no conflict of interest.

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Abstract: Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge were a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames were connected by four bridge beams. The bridge plate was made of a 10-cm-thick concrete plate. The bridge support of the reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus-type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm, meeting the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [42]. Bamboo is a renewable building material, such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboo, such as tensile strength, flexural strength, and other mechanical properties, can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3–4 years [6]. Bamboo is also very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures, such as warehouses, bridges, and village traditional houses, and for handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ±1500 species of bamboo [2]. In terms of its potential, in 2000 the total area of bamboo plants in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and

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1,414,000 ha of bamboo plant areas outside forest areas [27]. Arsad (2015) [27] revealed that in the Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha, with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [46]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the petung bamboo (*Dendrocalamus asper*) and ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with a high tensile strength. The use of bamboo as concrete reinforcement for simple construction is applied specifically in underdeveloped village areas that have a lot of bamboo.

Bamboo for concrete reinforcement is because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the tensile stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. Bamboo is suitable for use in tensile elements, simple construction, such as roof trusses, simple bridge trusses, simple house construction elements, and so on. Muhtar et al. (2018) [11] tested the pull-out of bamboo reinforcement with a layer of Sikadur®-752 and hose clamps embedded in a concrete cylinder, showing an increase in tensile stress of up to 240% compared to untreated bamboo reinforced concrete (BRC). A single BRC beam with a bamboo reinforcing area ratio of 4% exceeds the ultimate load of a steel-reinforced concrete (SRC) beam by 38.54% with a steel reinforcement area ratio of 0.89% [3]. However, bamboo also has weaknesses, which are being easily attacked by insects and having high water absorption. This study did not test for fungal and insect attacks, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [42] and Stebbings (1904) [45], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aim to remove the starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength; however, after drying it undergoes a transition from a brittle behavior to a very resilient behavior [28]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [44], the content of bamboo fiber (BF) treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength. Moe Thwe (2003) [51] conducted a study on the durability of bamboo with treatment using calcium hydroxide (CaOH2) to increase flexibility and durability.

In this study, the technology used to prevent decay and absorption, and the effect of a high pH, is to provide a Sikadur adhesive that is also a waterproof layer, and the basis is previous research that has been conducted by several researchers, including (1) Ghavami (2005) [1], who researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel; (2) Agarwal et al. (2014) [5], who researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sikadur 32 Gel. From the sticky strength test, it was found that the best adhesive was the Sikadur 32 Gel; (3) Lima Jr et al. (2008) [29], who experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength or Young's Modulus; (4) Javadian et al. (2016) [30], who did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of a high pH on the strength properties will be carried out in future studies; and (5) Muhtar et al. (2019) [3], who processed bamboo reinforcement by immersing in water for 1 month, coating with Sikadur®-752, and applying a hose clamp. The pull-out test results show that the bond-stress increases by 200% when compared to untreated bamboo. Sikadur®-752 adhesive is quite effective in

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preventing the occurrence of hygroscopic and hydrolysis processes between bamboo and concrete. The non-adhesive hose-clamp does not affect bond stress.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include (1) Ghavami (2005) [1], who concluded that bamboo can be used as a structural concrete element, including beams, windows, frames, and elements that experience bending stress; (2) Agarwal et al. (2014) [5], who conducted tests of treated bamboo reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements; (3) Sakaray et al. (2012) [31], who conducted a feasibility test for the moso-type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete; (4) Nayak et al. (2013) [32], who conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is three times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement; (5) Kaware et al. (2013) [33], who reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel; (6) Khan (2014) [34], who researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo reinforced concrete can be used successfully for structural and non-structural elements in building construction; (7) Rahman et al. (2011) [6], who conducted tests on bamboo reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete; (8) Sethia and Baradiya (2014) [35], who in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams; (9) Terai and Minami (2011) [36], who conducted a study on 11 bamboo reinforced concrete beams and tested them to check for flexural cracks and shear cracks, and concluded that the crack pattern of bamboo reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel-reinforced concrete beams; and (10) Muhtar (2020) [12], who conducted a flexural test on four beams with untreated bamboo reinforcement and treated with Sikadur®-752 and a hose clamp. The test results showed that the beam treated with Sikadur®-752 increased the load capacity by 164% when compared to the untreated reinforced bamboo. With the first treatment, bamboo is suitable for use as a simple construction concrete reinforcement.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [3-4], drying in free air [5,6], applying a waterproof layer [7], and sprinkled with sand, to modify the roughness of the bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [8], Sikadur 32 Gel [1,5], and Sikadur®-752 [4,7,9–12]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond stress of bamboo reinforcement [4]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [13–16], bamboo as column reinforcement [17–19], bamboo as slab reinforcement or panel reinforcement [20–22], and bamboo as a bridge frame reinforcement [23,24].

Muhtar [12] tested the flexural properties of four types of bridge beams with different treatments. The size of the bridge beam is 120 mm × 200 mm × 2100 mm with the area of tensile reinforcement ϱ = 4.68% and compressive reinforcement ϱ' = 1.88%. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of the bamboo reinforcement with adhesive, sand, and hose clamp can increase the bond stress and capacity of the bamboo reinforced concrete beam (BRC beam) [12]. The relationship between load vs. displacement is shown in Figure 1.

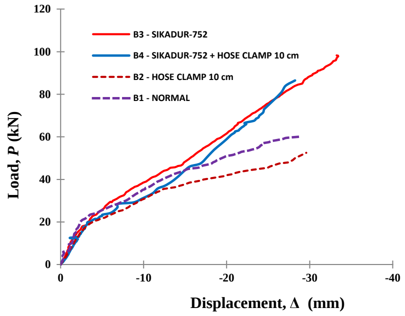

Figure 1. The relationship of load vs. deflection of the bamboo reinforced concrete (BRC) beam [12].

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Testing of bridge trusses has been carried out by several researchers, including bamboo as reinforcement for a truss easel [24] and as reinforcement for a bridge frame with a span of 3 m [23]. Dewi and Wonlele [24] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of the support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength; however, the collapse pattern still shows a bending effect [24].

Muhtar et al. [23] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", and one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has a higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of the load (*P*) vs. deflection (*Δ*) of the two bridge frames is shown in Figure 2.

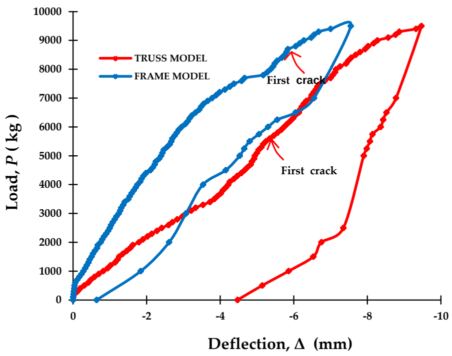

Figure 2. The relationship pattern of load vs. deflection of the bridge frame [23].

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The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [12]. In this study, strengthening of the reinforcement with hose clamps is only for tensile reinforcement, whereas in previous studies it was carried out for all reinforcements. Hose-clamp strengthening when the distance is too close together can reduce the elastic properties of the bamboo and reduce its capacity. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [23]. The reinforcement model on the lower side frame stem is installed with the concept of flexural reinforcement, whereas in previous studies it was carried out with the concept of truss reinforcement or symmetry, and their behavior shows flexural behavior. The basis for using the results of previous laboratory research is to control the results of the direct tests in the field. The novelty that is expected is (1) obtaining a prototype of the precast concrete reinforced concrete bridge; and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. The expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement, which could be applied to a simple frame bridge structure in underdeveloped village areas with local materials that are cheap, environmentally friendly, and acceptable.

The targets to apply this research to are underdeveloped villages with lots of bamboos. Bamboo is a new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including for reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used was the petung bamboo (*Dendrocalamus asper*), aged 3–5 years [4,5]. For the petung bamboo, the bamboo shoots are purplish-black, covered with hairs that are velvety brown to blackish. Petung bamboo is large, with a segment length 40–50 cm, diameter 12–18 cm, and a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, as per Brink (2008) in Wikipedia Indonesia (2016) [42]. The mechanical properties of petung bamboo are shown in Table 1. The tensile test for bamboo petung was based on ASTM D 143-94 [37].

Table 1. Mechanical properties of petung bamboo [47].

Mechanical Properties	
Tensile strength (MPa)	105 ± 8
Modulus of elasticity (GPa)	26 ± 5
Elongation of fault (%)	16 ± 1
Flexural strength (MPa)	153 ± 11
Hardness (VHN)	5 ± 1
Impact strength (J/mm^2)	0.15 ± 0.7

The bamboo part that is taken was 6–7 m from the base of the bamboo stem. The bamboo was cut and split into a bamboo reinforcement size of 15 × 15 mm^2. The bamboo to be used must be treated with the following steps: (a) the bamboo must be cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm × 15 mm × 2000 mm for bridge beam reinforcement, and 15 mm × 15 mm × 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm × 15 mm × 1100 mm, the top stem is 15 mm × 15 mm × 1100 mm, and the diagonal stem is 15 mm × 15 mm × 1300 mm; (b) the bamboo must be soaked in water for 1–2 months to remove the sugar content and prevent termites and insects, as shown in Figure 3 [45]; (c) it should be dried in free air until the moisture content is approximately 12%, as shown in Figure 4; (d) the bamboo reinforcement should be trimmed with a grinding machine according to the specified size, as shown in Figure 5; (e) one should provide a waterproof layer to reduce the occurrence of the hydrolysis process between the bamboo and concrete, as shown in Figure 6; (f) do sand sprinkling to modify the roughness of the bamboo reinforcement, as shown in Figure 7; and (g) stringing the bamboo reinforcement, as shown in Figure 8.

Ghavami (2005) [1] and Agarwal et al. (2014) [5] concluded that the best waterproof layer is Sikadur 32 Gel. Muhtar (2019) [3] treated bamboo with Sikadur®-752 and a hose clamp. The test results show that the adhesion strength increases up to 200% and the beam capacity increases 164% when compared to untreated bamboo reinforcement. The waterproof or adhesive layer used here was Sikadur®-752, produced by PT Sika Indonesia [3,10]. Sikadur®-752 is a solvent-free, two-component, super-low viscosity liquid, based on high strength epoxy resins—especially for injecting into the cavities and cracks in concrete. Usually used to fill and seal cavities and cracks in structural concrete, Sikadur®-752 is applied to the bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage. The thermal effect of Sikadur®-752 on bamboo reinforcement can be prevented by the moisture content of 12% in bamboo. In determining the strength of the bamboo, a 12% moisture content in the air-dry condition has been considered as a reference standard [48], and the temperature does not significantly affect the loss of stiffness [49]. Chemical treatment of bamboo helps increase the durability of the bamboo fibers and reduces the moisture absorption of the bamboo fibers [50].

Table 2. The specifications of Sikadur®-752 [41].

Components	Properties
Color	Yellowish
Density	Approx. 1.08 kg/L
Mixing Ratio, by weight/volume	2:1
Pot life at +30 °C	35 min
Compressive strength	62 N/mm^2 at 7 days (ASTM D-695) 64 N/mm^2 at 28 days
Tensile strength	40 N/mm^2 at 28 days (ASTM D-790)
Tensile adhesion strength	2 N/mm^2 (Concrete failure, over mechanically prepared concrete surface)
Coefficient of thermal expansion	−20 °C to +40 °C, 89 × 10^{-6} per °C
Modulus of elasticity	1060 N/mm^2

The hose clamp used had a diameter of ¾″, made in Taiwan [3,12]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm in diameter, with a f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of the bamboo (E_b) was 17,236 MPa, with a tensile strength of 127 N/mm^2 [3], and the modulus of steel elasticity (E_s) was 207,736 MPa [3]. The concrete mixture used was Portland Pozzolana Cement (PPC), with a pH of 7, as well as sand, coarse aggregate, and water with a mixed proportion of 1.81:2.82:0.52, as shown in Table 3. The average compressive strength of the concrete was 31.31 MPa at the age of 28 days. The process of treating the bamboo to assembling the bamboo reinforcement can be seen in Figures 3–8.

Table 3. The mix composition of the concrete.

The Concrete Mix Design	Cement (PPC)	Fine Aggregate	Coarse Aggregate	Water
	Kg/m^3			
Material per m^3	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

Figure 3. Take bamboo from the soaking.

Figure 4. Drying bamboo in free air.

Figure 5. Tidy up the bamboo according to size.

Figure 6. Give a waterproof coating.

Figure 7. Sand sprinkling on bamboo reinforcement.

Figure 8. Stringing the bamboo reinforcement.

2.2. Methods

The dimensions of the bridge were a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge was 280 cm. Two bridge frames were connected by four bridge beams. Each end of the bridge beam was connected to the knot point with two bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of the joints between the beam and precast bridge frame are shown in Figures 10 and 11. The bridge supports were made of reinforced concrete with the assumption of hinge support and a rubber

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bearing assuming roller support. The bridge plate was a 10-cm-thick concrete plate with 0.3-mm-thick spandex. The shape and model of the precast bridge of the bamboo reinforced concrete frame are described in Figure 12. Details of the reinforcement of the precast bridge beams are shown in Figure 13. Details of the reinforcement of the bridge frame are shown in Figures 14 and 15 and Table 4.

The design concept of the bamboo reinforced concrete beams follows Ghavami (2005) [1] and Muhtar (2020) [12], as shown in Figure 9. The balance of the concrete compressive force ($C = C_{b'} + C_c$) and the tensile force (T) must be met, as shown in Figure 9. The tensile strength of the bamboo reinforcement (T) was obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo reinforced concrete beams was due to the breaking of the bonds between the bamboo and concrete.

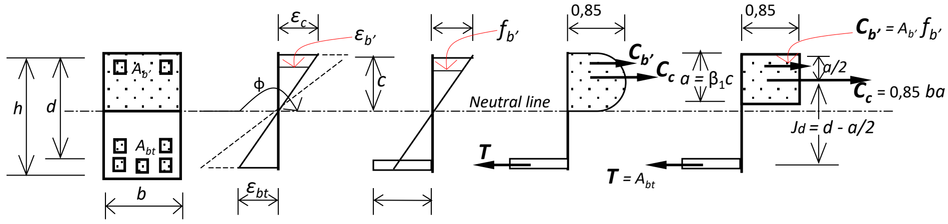

Figure 9. Stress–strain distribution diagram in a BRC beam [1,12].

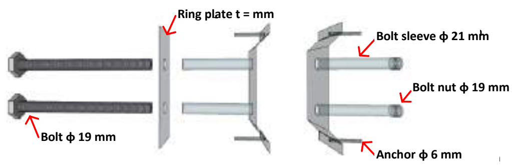

Figure 10. Details of the ring plate and bolt sleeve.

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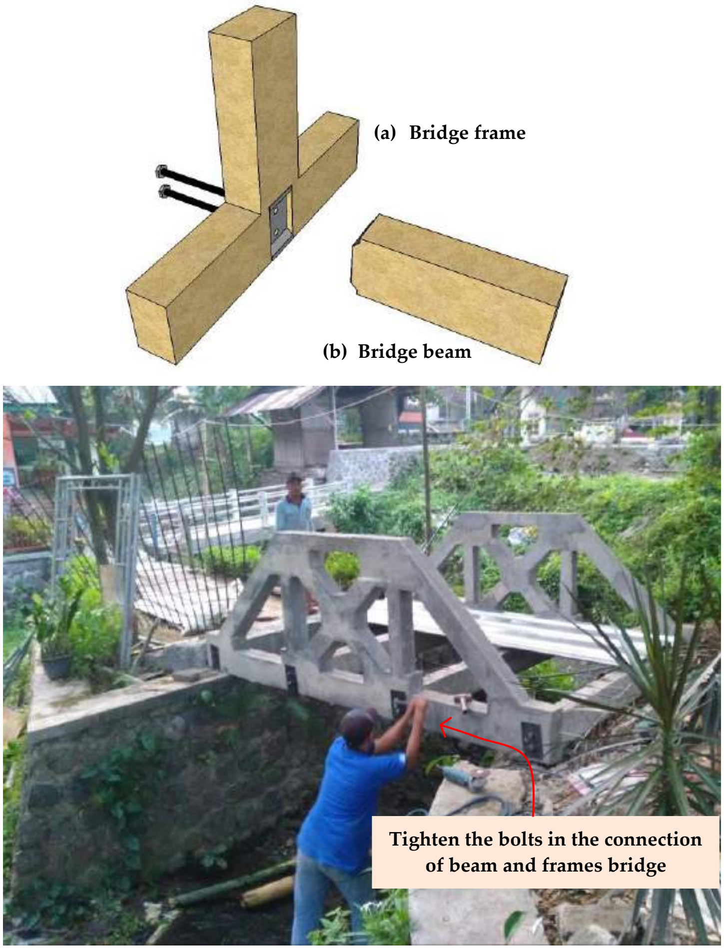

Figure 11. Models and applications of the precast connections.

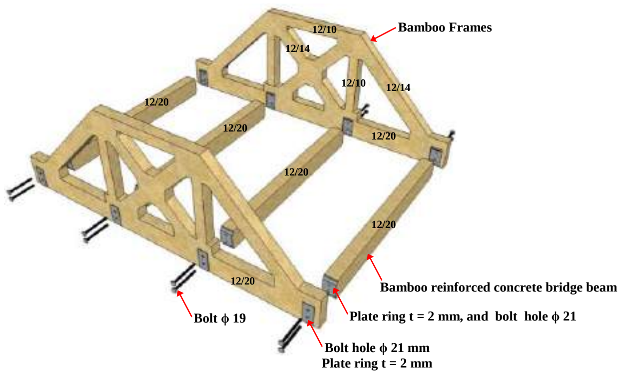

Figure 12. Model of the precast bridge made from bamboo reinforced concrete.

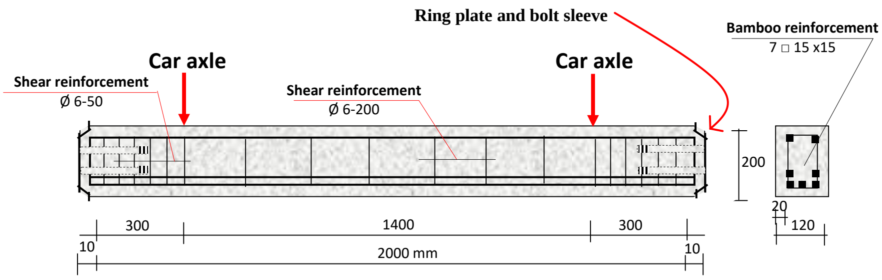

Figure 13. Details of the precast bridge beam reinforcement [12].

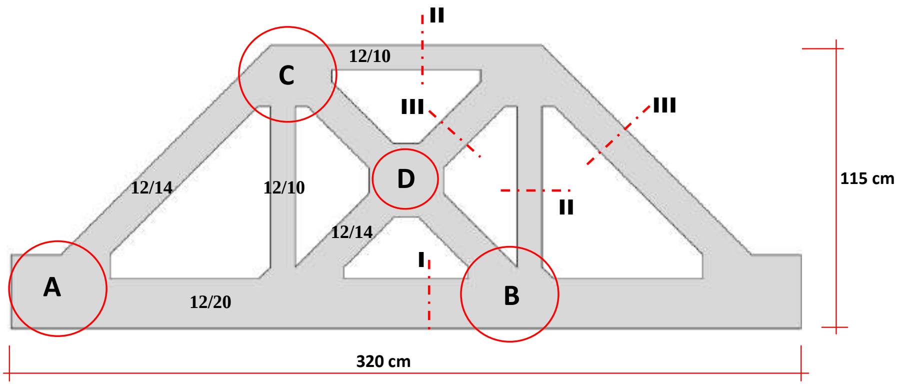

Figure 14. Details of the precast bridge frame [23].

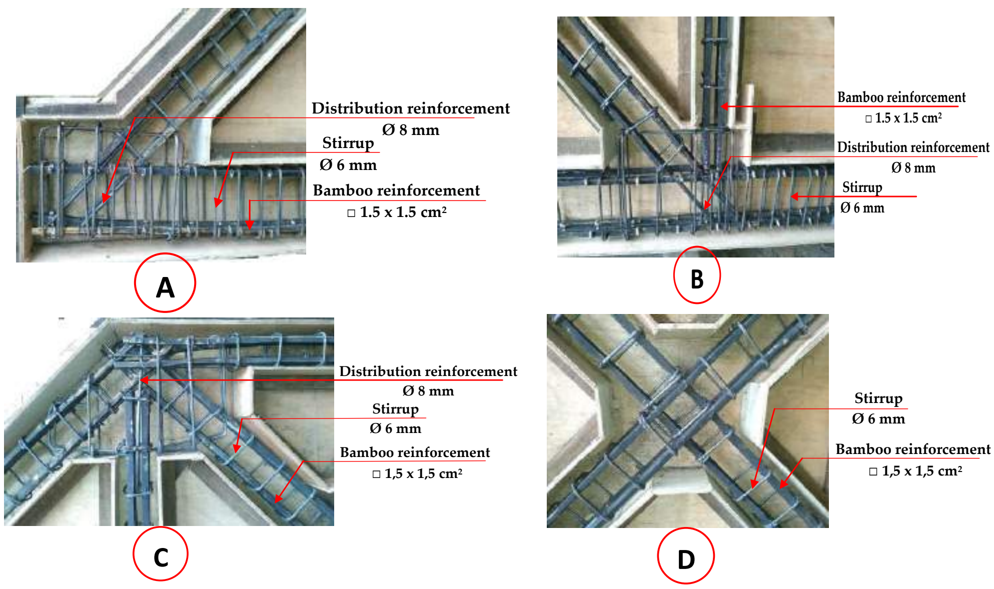

Figure 15. Details of the knot reinforcement for the bridge frames [23].

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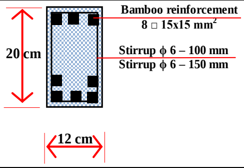
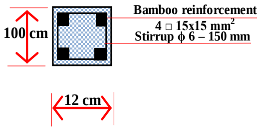
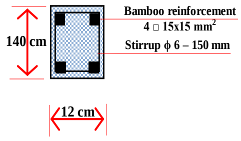
Table 4. Details of the bridge frame reinforcement [23].

Model	I (Shown in Figure 14)	II (Shown in Figure 14)	III (Shown in Figure 14)
Rigid portal model or "frame model"			

Testing of the precast bridges with the bamboo reinforced concrete frames was carried out directly with a load of a minibus-type vehicle. The load was given in stages and levels, starting from a zero load, Brio carload without passengers, Brio carload full of passengers, and Avanza carload full of passengers, as shown in Figure 16. The stage of reading the response variable was carried out when the axle of the car was at the coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm, and 300 cm from the support, as shown in Figure 17. Tests were carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, four LVDTs (Linear Variable Displacement Transducers) were installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, six pieces of LVDTs were installed, two pieces of LVDTs were installed in the middle of the side frame span, and four LVDTs were installed on the side of the four ends of the beam. The performance test settings for the precast bridges of the bamboo reinforced concrete frames are described in Figure 18.

The weights of the Brio and Avanza cars were calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight was based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

Table 5. Specifications and weight of the minibus car.

Type of Car	Length	Height	Width	Wheelbase	Empty Weight or One Driver	Passenger Capacity	Weight with Full Passenger
	mm	mm	mm	mm	kg	persons	kg
Brio	3800	1485	1680	2655	930–965	5	1280
Avanza	4190	1695	1660	2655	1045–1095	7	1550

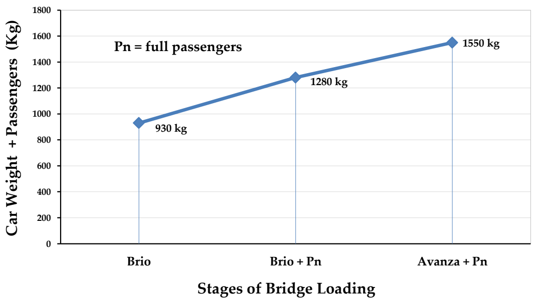


Figure 16. Loading stage of the precast bridges with a bamboo reinforced concrete frame.

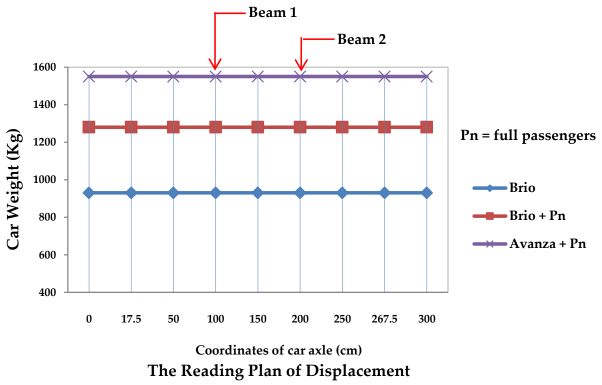


Figure 17. The coordinates of the reading points of the displacement and deformation.

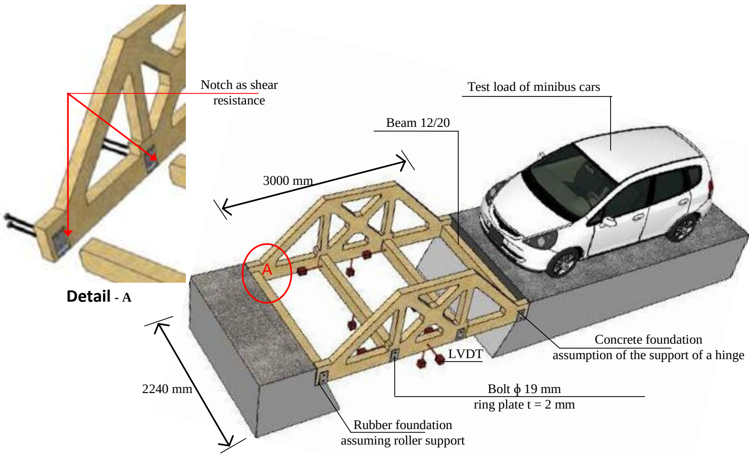


Figure 18. Arrangement of the testing of the bamboo reinforced concrete frame precast bridges.

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers, including Hidalgo (1992) in Sattar (1995) [43], Ghavami (2005) [1], Rong (2007) [40], and Lima Jr et al. (2008) [29]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [43] reported that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that, after testing, the bamboo reinforced concrete beams were left in the open air at the PUC Rio Brazil university campus; the bamboo reinforcements from the treated beams showed that the bond with the concrete was still in satisfactory condition after 15 years. Rong (2007) [40], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, stated that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement as the level of durability is good. Lima Jr et al. (2008) [29] experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength or Young's Modulus. This is an important factor in the material for use as concrete reinforcement.

2.3. The Numerical Method Used

Determining the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis was written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack was done by using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo reinforced concrete is shown in Equations (1) and (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (*E*). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom, as shown in Figure 19. The stress–strain relationship for the field stress problem has the form of an equation, such as Equation (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \quad (1)$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \quad (2)$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (3)$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \quad (4)$$

where E is the modulus of elasticity and ν is the Poisson's ratio. The principal stresses in two dimensions are calculated by Equation (4). The Fortran PowerStation 4.0 programming language for triangle elements is shown at the following link: https://bit.ly/3l1oU0d.

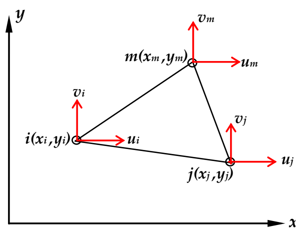


Figure 19. The degrees of freedom of the triangular element.

3. Results

Specifications for precast bridges of the bamboo reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car full of passengers. The test was carried out after several stages of work were done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, and completing or finishing the bridge. Recording of the test results started when the front axle of the minibus car was right on the hinge support and ended when the rear axle of the minibus car was right on the support of the roller. The test result data are shown in Table 7.

The security measure during the test was to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the

LVDT tool. Besides, the bridge was planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test was carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and the deformation that occurred was deflection and elastic deformation. The critical load (Pcr) or initial crack load was 2.1 tons and the maximum test load for the minibuses was 1.55 tons.

Figures 20–25 show the beam displacement and the bridge frame with the minibus Brio car, the Brio full of passengers, and the AVANZA full of passengers. The maximum displacement with the load of the Brio car occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for the beam displacement. While, the maximum displacement with a full passenger Brio car occurred when the position of the front axle was at coordinates 200 cm and the rear axle was at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for the beam displacement. The maximum displacement with a full passenger AVANZA car load occurred when the front axle position was outside the bridge coordinates, which was 115 cm from the roller support, and the rear axle was at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for the displacement beam.

Based on the AASHTO [38] and RSNI T-12-2004 standards [25], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo reinforced concrete frame bridge meets the requirements based on the AASHTO [38] and RSNI T-12-2004 standards [25].

Table 6. Geometry and specifications of the precast bridges with a bamboo reinforced concrete frame.

Bridge span:	3 m
Foundation:	River stone
Bridge support:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam:	- Dimensions of the bridge beam 12 × 20 cm^2, tensile reinforcement (ϱ) = 4.688% and compressive reinforcement (ϱ') = 1.875% - Hose-clamp d = ¾ attached to the end of the bamboo reinforcement instead of hooks. - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand
Connection type:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model:	Rigid portal model or "frame model"
Bridge slab:	- 10 cm thick slab + spandex t = 0.3 mm. - Slab reinforcement using bamboo 1.5 × 1.5 cm^2 with a distance of 10 cm
Displacement and deformation of permit:	Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge with bamboo reinforced concrete frames.

Bridge Load	Displacement and Deformation						
	Frame 1		Frame 2		Beam 1		Beam 2
	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)
Brio 930 kg	0.2	0.03	0.04	0.04	0.06	0.01	0.14
Brio + Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza + Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of the vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured as the direction of the horizontal of the cross-section.

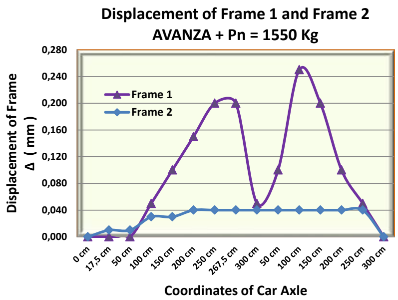


Figure 20. Displacement of the frame with loads of the Avanza car full of passengers.

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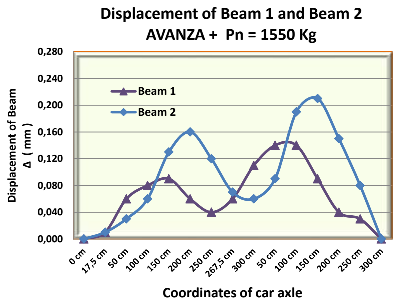

Figure 21. Displacement of the beam with loads of the Avanza car full of passengers.

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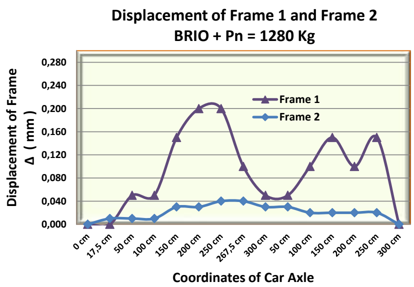

Figure 22. Displacement of the frame with loads of the BRIO car full of passengers.

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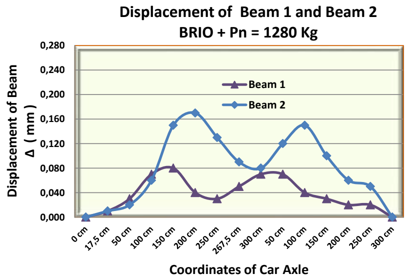

Figure 23. Displacement of the beam with loads of the BRIO car full of passengers.

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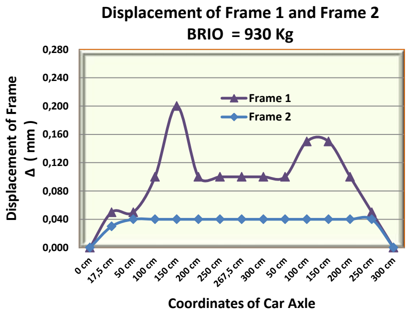

Figure 24. Displacement of the frame with loads of the BRIO car with no passengers.

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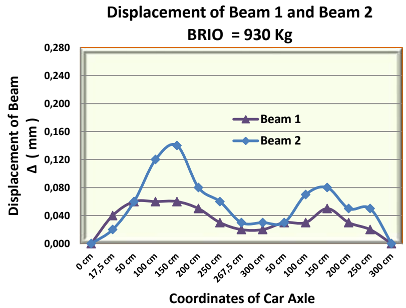

Figure 25. Displacement of the beam with loads of the BRIO car with no passengers.

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Figure 26 shows the deformation of the bridge beam of the bamboo reinforced concrete with a load of Brio minibuses, the Brio car full of passengers, and the Avanza car full of passengers. From Figure 26 and Table 7, we see that the maximum deformation occurs in the beam with the load of the Avanza car with a full passenger load, which is when the position of the front axle is outside the coordinates of the bridge, which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with the deformation of the beam being 0.20 mm.

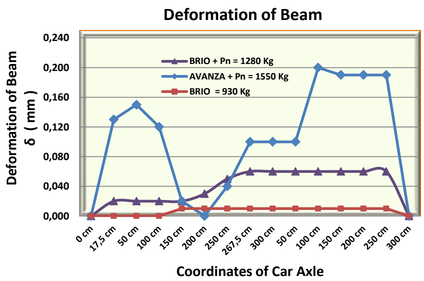

Figure 26. Deformation of the beam of the precast bridge of bamboo reinforced concrete.

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Figures 27–29 show the deformation of the bridge frame with the load of the Brio minibus, Brio car full of passengers, and the Avanza car full of passengers. The maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with a frame deformation of 0.04 mm.

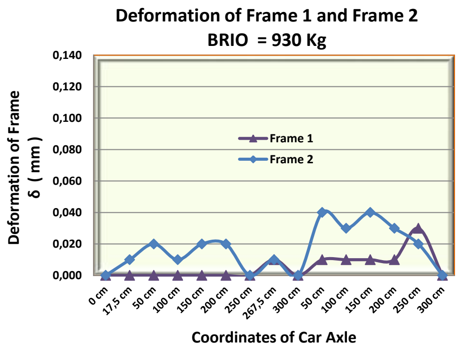

Figure 27. Deformation of the frame with loads of the Brio car with no passengers.

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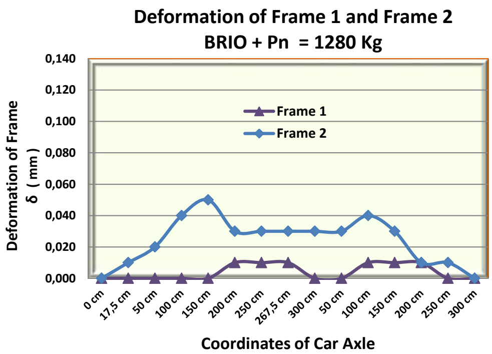

Figure 28. Deformation of the frame with loads of the Brio car full of passengers.

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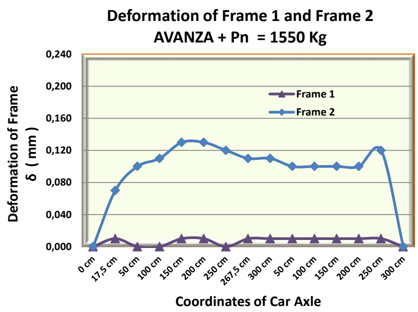

Figure 29. Deformation of the frame with loads of the Avanza car full of passengers.

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The maximum frame deformation with the load of the brio car full of passengers occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the hinge support, with a deformation of 0.05 mm. The maximum deformation of the frame with the load of the Avanza car full of passengers occurred when the position of the front axle was at the coordinates of the bridge of 150 cm, and the rear axle was at a distance of 115 cm from the hinge support, with a deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to a static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured in the horizontal direction of the cross section. Measurements were made by installing LVDTs (Linear Variable Displacement Transducers) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams, as shown in Figure 30.

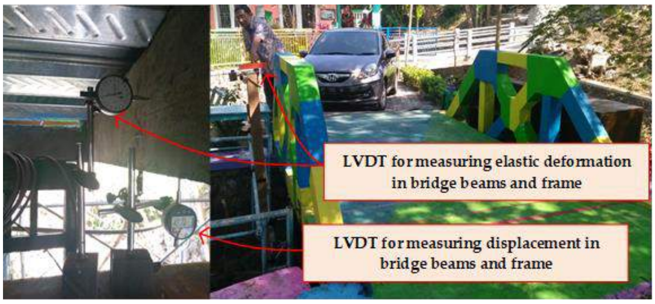

Figure 30. Measuring the elastic displacement and deformation.

The accuracy of the deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site, such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce the deformation and increase the deflection of the bridge beams. Figures 21 and 26 at the 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at the coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle; that is, the deformation continues to increase, respectively, at the front car axle and rear car axle. However, the accuracy of the deformation measurements needs attention as to the many determinants of accuracy that exist.

Figures 27 and 28 shows that the minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span or at the 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate; as shown in Figure 27, the coordinates at 250 cm convey inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [38] and RSNI T-12-2004 standards [25], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo reinforced concrete frame meet the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25]. However, the relationship of load vs. displacement of the beam and the frame results from the field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and Surfer 9.8 software [26] based on laboratory test results. Simulations were carried out as control and validation of the experimental data. The bridge frame test simulation was carried out at the first crack load stage, which was 87 kN based on the frame loading capacity of only 100 kN. The discretization of the bamboo reinforced concrete bridge frame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figures 32 and 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [23], and with the field test results as shown in Figure 34. Figure 33 shows displacement in the X-direction; the green color shows the minimum displacement, and the orange and blue colors show the maximum positive and negative displacement, respectively. FEM analysis modeling on the bamboo reinforced concrete frames can be seen in Item 2.3 of the numerical method used.

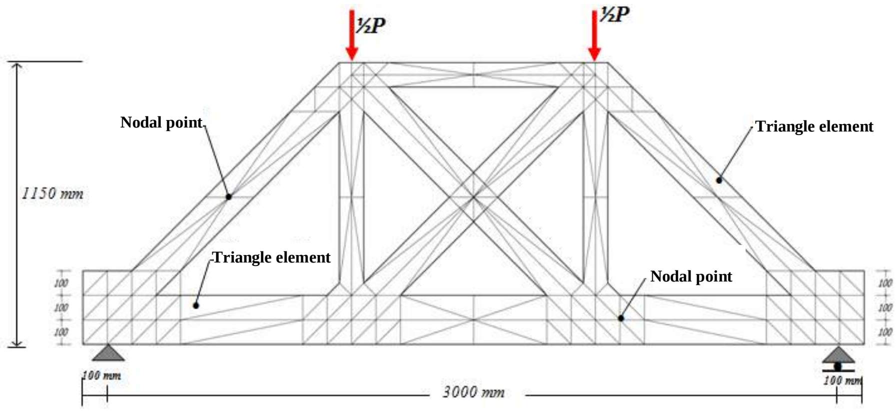

Figure 31. Discretization of the bamboo reinforced concrete bridge frames.

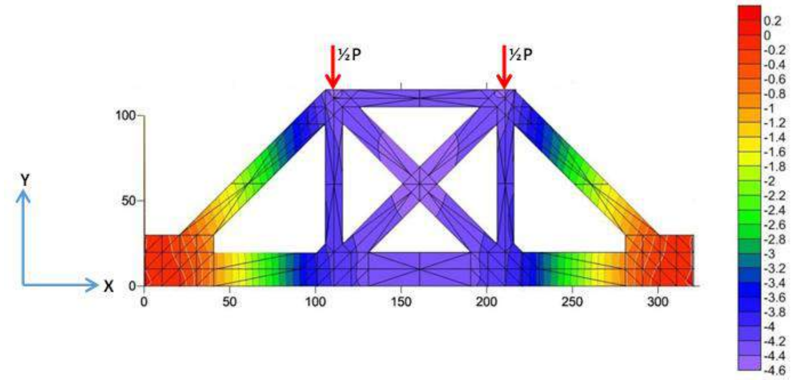

Figure 32. The displacement of Y-direction of the bridge frame.

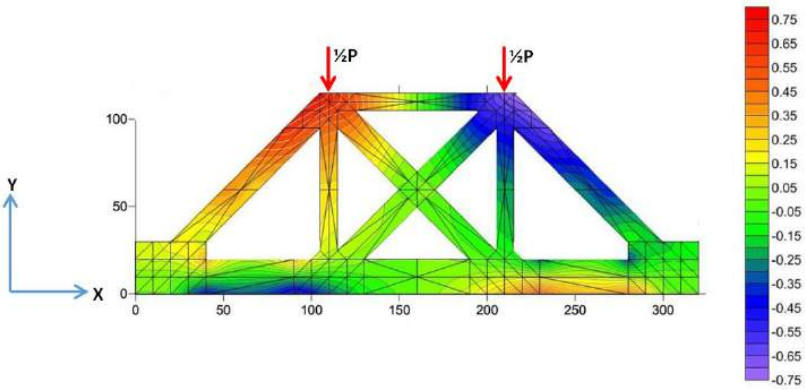

Figure 33. The displacement in the X-direction of the bridge frame.

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [7]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of the beams and bridge frames was analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [12,23], and the results of field experiments as shown in Figure 34. Control was carried out at the maximum load point of the bamboo reinforced concrete precast frame bridge test in the field, which was 15.5 kN, as shown in Figures 35 and 36. Documentation of the direct test of the bamboo reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of the aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, the SNI SNI-07-SE-2015 [39] dynamic analysis needed to be carried out for bridge types with a complex behavior, one of which was the main span exceeding 200 m. In this study, the bridge width is 2.24 m and the bridge span is 3.20 m, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements of AASHTO [38] and RSNI T-12-2004 [25], which is Δ_{max} = L/800 = 3.75 mm.

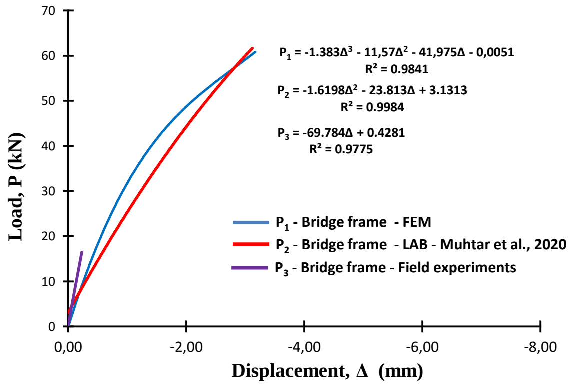

Figure 34. The relationship of load vs. displacement of the bridge frame.

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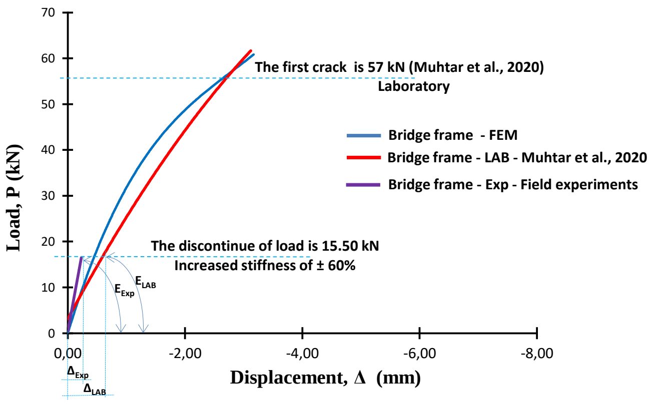

Figure 35. The relationship of load vs. displacement of the bridge frame from the laboratory test results, FEM results, and field experiment results.

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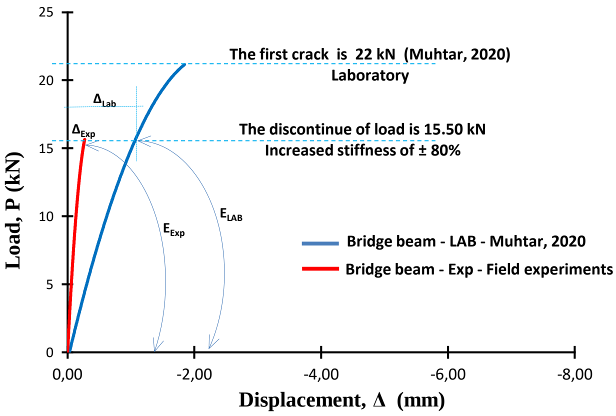

Figure 36. The relationship of load vs. displacement of the bridge beam from the laboratory test results and field experiment results.

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The next step was validating the stiffness of the beam and bridge trusses. The main principle is that the bridge must be in a service condition, with a Serviceability Limit State (SLS) load. The elements of the bridge structure should not be subjected to cracks, deflection, or vibrations causing user discomfort. The allowable deflections are those that are elastic deflection and do not cause the crack. Stiffness is the main parameter of structural resistance. Therefore, the stiffness of the field test results needs to be validated by the stiffness of the laboratory test results. Load–displacement relationship diagrams of the experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results, and the displacement of the field experiments results of the bamboo reinforced concrete frame precast bridge at a stop load of 15.50 kN, the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame and 4.07 for the bridge beam. Figures 35 and 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of the laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs when the rear wheel is at the center of the span at the 150 cm coordinates and the front wheel is at the 415.5 cm coordinates (the front wheel is outside the bridge). While, the maximum displacement of the frame occurs when the rear wheel is at the 100 cm coordinates and the front wheel is at the 365.5 cm coordinates (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely, the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load of P = 15.5 kN, the stiffness of the bridge beam increased ±80% during the bridge test when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ±60% during the bridge test when compared to the frame stiffness of the laboratory results.

Author Contributions: The following statements should be used "conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Ledokombo District, Jember Regency, Indonesia, as the 2020 PPM Program. PPM activities can be seen at the following link: https://youtu.be/jq1YCEpBDfE.

Conflicts of Interest: The author declares no conflict of interest.

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Abstract: Bamboo is an inexpensive, environmentally friendly, and renewable building material that thrives in Indonesia. Bamboo has a high tensile strength but also has weaknesses, namely, it is easily attacked by insects and has high water absorption. Utilization of bamboo as a precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge were a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames were connected by four bridge beams. The bridge plate was made of a 10-cm-thick concrete plate. The bridge support of the reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus-type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm, meeting the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [2]. Bamboo is a renewable building material, such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboo, such as tensile strength, flexural strength, and other mechanical properties, can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3–4 years [3]. Bamboo is also very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures, such as warehouses, bridges, and village traditional houses, and for handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ±1500 species of bamboo [4]. In terms of its potential, in 2000 the total area of bamboo plants in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and

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1,414,000 ha of bamboo plant areas outside forest areas [5]. Arsad (2015) [5] revealed that in the Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha, with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [6]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the petung bamboo (*Dendrocalamus asper*) and ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with a high tensile strength. The use of bamboo as concrete reinforcement for simple construction is applied specifically in underdeveloped village areas that have a lot of bamboo.

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Bamboo for concrete reinforcement is because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the tensile stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. Bamboo is suitable for use in tensile elements, simple construction, such as roof trusses, simple bridge trusses, simple house construction elements, and so on. Muhtar et al. (2018) [7] tested the pull-out of bamboo reinforcement with a layer of Sikadur®-752 and hose clamps embedded in a concrete cylinder, showing an increase in tensile stress of up to 240% compared to untreated bamboo reinforced concrete (BRC). A single BRC beam with a bamboo reinforcing area ratio of 4% exceeds the ultimate load of a steel-reinforced concrete (SRC) beam by 38.54% with a steel reinforcement area ratio of 0.89% [8]. However, bamboo also has weaknesses, which are being easily attacked by insects and having high water absorption. This study did not test for fungal and insect attacks, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [2] and Stebbings (1904) [9], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aim to remove the starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength; however, after drying it undergoes a transition from a brittle behavior to a very resilient behavior [10]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [11], the content of bamboo fiber (BF) treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength. Moe Thwe (2003) [12] conducted a study on the durability of bamboo with treatment using calcium hydroxide (CaOH2) to increase flexibility and durability.

In this study, the technology used to prevent decay and absorption, and the effect of a high pH, is to provide a Sikadur adhesive that is also a waterproof layer, and the basis is previous research that has been conducted by several researchers, including (1) Ghavami (2005) [1], who researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel; (2) Agarwal et al. (2014) [13], who researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sikadur 32 Gel. From the sticky strength test, it was found that the best adhesive was the Sikadur 32 Gel; (3) Lima Jr et al. (2008) [14], who experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength or Young's Modulus; (4) Javadian et al. (2016) [15], who did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of a high pH on the strength properties will be carried out in future studies; and (5) Muhtar et al. (2019) [8], who processed bamboo reinforcement by immersing in water for 1 month, coating with Sikadur®-752, and applying a hose clamp. The pull-out test results show that the bond-stress increases by 200% when compared to untreated bamboo. Sikadur®-752 adhesive is quite effective in preventing the occurrence of hygroscopic and hydrolysis processes between bamboo and concrete. The non-adhesive hose-clamp does not affect bond stress.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include (1) Ghavami (2005) [1], who concluded that bamboo can be used as a structural concrete element, including beams, windows, frames, and elements that experience bending stress; (2) Agarwal et al. (2014) [13], who conducted tests of treated bamboo reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements; (3) Sakaray et al. (2012) [16], who conducted a feasibility test for the moso-type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete; (4) Nayak et al. (2013) [17], who conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is three times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement; (5) Kaware et al. (2013) [18], who reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel; (6) Khan (2014) [19], who researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo reinforced concrete can be used successfully for structural and non-structural elements in building construction; (7) Rahman et al. (2011) [3], who conducted tests on bamboo reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete; (8) Sethia and Baradiya (2014) [20], who in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams; (9) Terai and Minami (2011) [21], who conducted a study on 11 bamboo reinforced concrete beams and tested them to check for flexural cracks and shear cracks, and concluded that the crack pattern of bamboo reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel-reinforced concrete beams; and (10) Muhtar (2020) [22], who conducted a flexural test on four beams with untreated bamboo reinforcement and treated with Sikadur®-752 and a hose clamp. The test results showed that the beam treated with Sikadur®-752 increased the load capacity by 164% when compared to the untreated reinforced bamboo. With the first treatment, bamboo is suitable for use as a simple construction concrete reinforcement.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [8,23], drying in free air [3,13], applying a waterproof layer [24], and sprinkled with sand, to modify the roughness of the bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [25], Sikadur 32 Gel [1,13], and Sikadur®-752 [7,22-24,26-27]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond stress of bamboo reinforcement [23]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [28–31], bamboo as column reinforcement [17–34], bamboo as slab reinforcement or panel reinforcement [35–37], and bamboo as a bridge frame reinforcement [38-39].

Muhtar [22] tested the flexural properties of four types of bridge beams with different treatments. The size of the bridge beam is 120 mm × 200 mm × 2100 mm with the area of tensile reinforcement ϱ = 4.68% and compressive reinforcement ϱ' = 1.88%. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of the bamboo reinforcement with adhesive, sand, and hose clamp can increase the bond stress and capacity of the bamboo reinforced concrete beam (BRC beam) [22]. The relationship between load vs. displacement is shown in Figure 1.

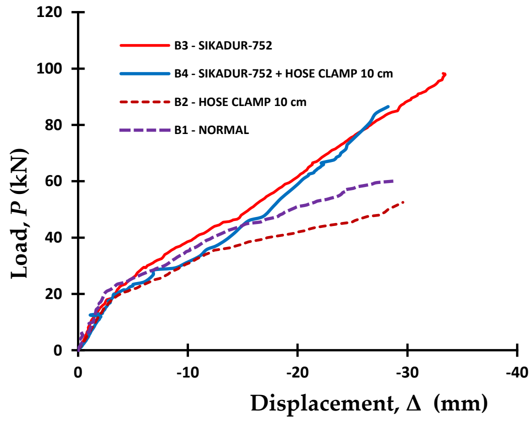

Figure 1. The relationship of load vs. deflection of the bamboo reinforced concrete (BRC) beam [22].

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Testing of bridge trusses has been carried out by several researchers, including bamboo as reinforcement for a truss easel [39] and as reinforcement for a bridge frame with a span of 3 m [38]. Dewi and Wonlele [39] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of the support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength; however, the collapse pattern still shows a bending effect [39].

Muhtar et al. [38] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", and one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has a higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of the load (*P*) vs. deflection (*Δ*) of the two bridge frames is shown in Figure 2.

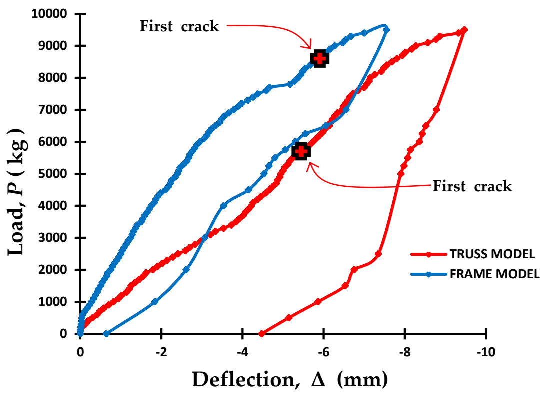

Figure 2. The relationship pattern of load vs. deflection of the bridge frame [38].

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The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [22]. In this study, strengthening of the reinforcement with hose clamps is only for tensile reinforcement, whereas in previous studies it was carried out for all reinforcements. Hose-clamp strengthening when the distance is too close together can reduce the elastic properties of the bamboo and reduce its capacity. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [38]. The reinforcement model on the lower side frame stem is installed with the concept of flexural reinforcement, whereas in previous studies it was carried out with the concept of truss reinforcement or symmetry, and their behavior shows flexural behavior. The basis for using the results of previous laboratory research is to control the results of the direct tests in the field. The novelty that is expected is (1) obtaining a prototype of the precast concrete reinforced concrete bridge; and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. The expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement, which could be applied to a simple frame bridge structure in underdeveloped village areas with local materials that are cheap, environmentally friendly, and acceptable.

The targets to apply this research to are underdeveloped villages with lots of bamboos. Bamboo is a new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including for reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used was the petung bamboo (*Dendrocalamus asper*), aged 3–5 years [13,23]. For the petung bamboo, the bamboo shoots are purplish-black, covered with hairs that are velvety brown to blackish. Petung bamboo is large, with a segment length 40–50 cm, diameter 12–18 cm, and a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, as per Brink (2008) in Wikipedia Indonesia (2016) [2]. The mechanical properties of petung bamboo are shown in Table 1. The tensile test for bamboo petung was based on ASTM D 143-94 [40].

Table 1. Mechanical properties of petung bamboo [41].

Mechanical Properties	
Tensile strength (MPa)	105 ± 8
Modulus of elasticity (GPa)	26 ± 5
Elongation of fault (%)	16 ± 1
Flexural strength (MPa)	153 ± 11
Hardness (VHN)	5 ± 1
Impact strength (J/mm^2)	0.15 ± 0.7

The bamboo part that is taken was 6–7 m from the base of the bamboo stem. The bamboo was cut and split into a bamboo reinforcement size of 15 × 15 mm^2. The bamboo to be used must be treated with the following steps: (a) the bamboo must be cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm × 15 mm × 2000 mm for bridge beam reinforcement, and 15 mm × 15 mm × 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm × 15 mm × 1100 mm, the top stem is 15 mm × 15 mm × 1100 mm, and the diagonal stem is 15 mm × 15 mm × 1300 mm; (b) the bamboo must be soaked in water for 1–2 months to remove the sugar content and prevent termites and insects, as shown in Figure 3 [9]; (c) it should be dried in free air until the moisture content is approximately 12%, as shown in Figure 4; (d) the bamboo reinforcement should be trimmed with a grinding machine according to the specified size, as shown in Figure 5; (e) one should provide a waterproof layer to reduce the occurrence of the hydrolysis process between the bamboo and concrete, as shown in Figure 6; (f) do sand sprinkling to modify the roughness of the bamboo reinforcement, as shown in Figure 7; and (g) stringing the bamboo reinforcement, as shown in Figure 8.

Ghavami (2005) [1] and Agarwal et al. (2014) [13] concluded that the best waterproof layer is Sikadur 32 Gel. Muhtar (2019) [8] treated bamboo with Sikadur®-752 and a hose clamp. The test results show that the adhesion strength increases up to 200% and the beam capacity increases 164% when compared to untreated bamboo reinforcement. The waterproof or adhesive layer used here was Sikadur®-752, produced by PT Sika Indonesia [8,27]. Sikadur®-752 is a solvent-free, two-component, super-low viscosity liquid, based on high strength epoxy resins—especially for injecting into the cavities and cracks in concrete. Usually used to fill and seal cavities and cracks in structural concrete, Sikadur®-752 is applied to the bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage. The thermal effect of Sikadur®-752 on bamboo reinforcement can be prevented by the moisture content of 12% in bamboo. In determining the strength of the bamboo, a 12% moisture content in the air-dry condition has been considered as a reference standard [42], and the temperature does not significantly affect the loss of stiffness [43]. Chemical treatment of bamboo helps increase the durability of the bamboo fibers and reduces the moisture absorption of the bamboo fibers [44].

Table 2. The specifications of Sikadur®-752 [45].

Components	Properties
Color	Yellowish
Density	Approx. 1.08 kg/L
Mixing Ratio, by weight/volume	2:1
Pot life at +30 °C	35 min
Compressive strength	62 N/mm^2 at 7 days (ASTM D-695) 64 N/mm^2 at 28 days
Tensile strength	40 N/mm^2 at 28 days (ASTM D-790)
Tensile adhesion strength	2 N/mm^2 (Concrete failure, over mechanically prepared concrete surface)
Coefficient of thermal expansion	−20 °C to +40 °C, 89 × 10^{-6} per °C
Modulus of elasticity	1060 N/mm^2

The hose clamp used had a diameter of ¾”, made in Taiwan [8,22]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm in diameter, with a f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of the bamboo (E_b) was 17,236 MPa, with a tensile strength of 127 N/mm^2 [8], and the modulus of steel elasticity (E_s) was 207,736 MPa [8]. The concrete mixture used was Portland Pozzolana Cement (PPC), with a pH of 7, as well as sand, coarse aggregate, and water with a mixed proportion of 1.81:2.82:0.52, as shown in Table 3. The average compressive strength of the concrete was 31.31 MPa at the age of 28 days. The process of treating the bamboo to assembling the bamboo reinforcement can be seen in Figures 3–8.

Table 3. The mix composition of the concrete.

The Concrete Mix Design	Cement (PPC)	Fine Aggregate	Coarse Aggregate	Water
	Kg/m^3			
Material per m^3	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

Figure 3. Take bamboo from the soaking.

Figure 4. Drying bamboo in free air.

Figure 5. Tidy up the bamboo according to size.

Figure 6. Give a waterproof coating.

Figure 7. Sand sprinkling on bamboo reinforcement.

Figure 8. Stringing the bamboo reinforcement.

2.2. Methods

The dimensions of the bridge were a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge was 280 cm. Two bridge frames were connected by four bridge beams. Each end of the bridge beam was connected to the knot point with two bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of the joints between the beam and precast bridge frame are shown in Figures 9 and 10. The bridge supports were made of reinforced concrete with the assumption of hinge support and a rubber

Comment [M10]: The Figure number is changed, from number "10 and 11" to "9 and 10" bearing assuming roller support. The bridge plate was a 10-cm-thick concrete plate with 0.3-mm-thick spandex. The shape and model of the precast bridge of the bamboo reinforced concrete frame are described in Figure 12. Details of the reinforcement of the precast bridge beams are shown in Figure 13. Details of the reinforcement of the bridge frame are shown in Figures 14 and 15 and Table 4.

The design concept of the bamboo reinforced concrete beams follows Ghavami (2005) [1] and Muhtar (2020) [22], as shown in Figure 11. The balance of the concrete compressive force (C = Cb + Cc) and the tensile force (T) must be met, as shown in Figure 9. The tensile strength of the bamboo reinforcement (T) was obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo reinforced concrete beams was due to the breaking of the bonds between the bamboo and concrete.

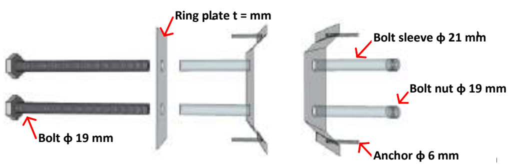

Figure 9. Details of the ring plate and bolt sleeve.

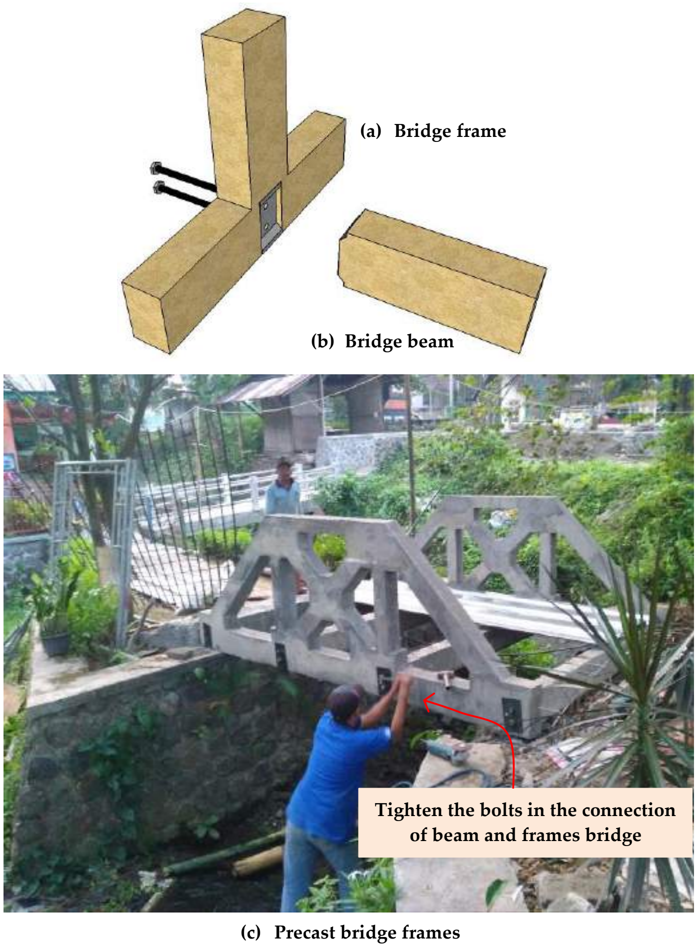

Figure 10. Models and applications of the precast connections.

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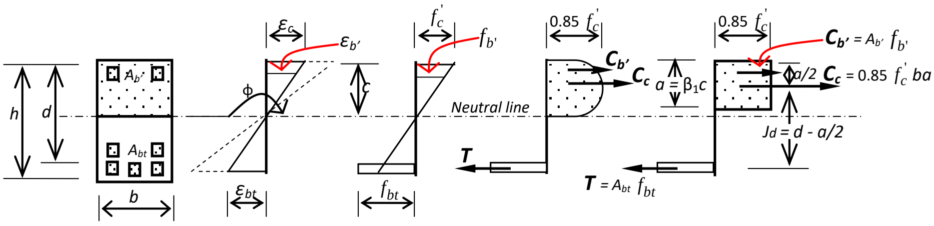

Figure 11. Stress–strain distribution diagram in a BRC beam [1,22].

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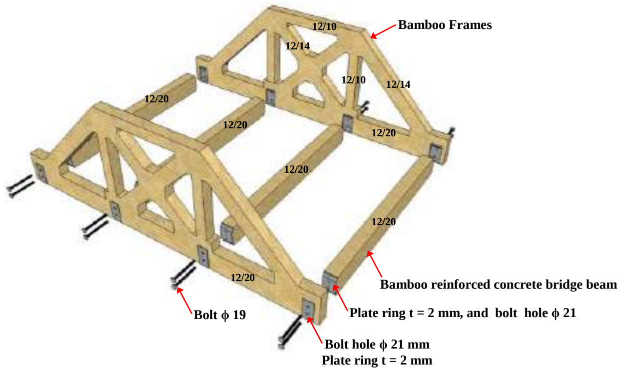


Figure 12. Model of the precast bridge made from bamboo reinforced concrete.

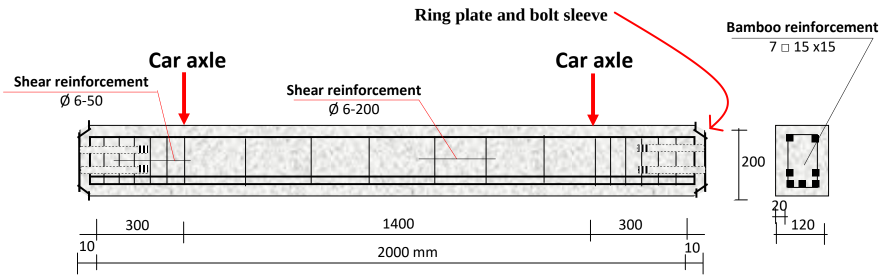


Figure 13. Details of the precast bridge beam reinforcement [22].

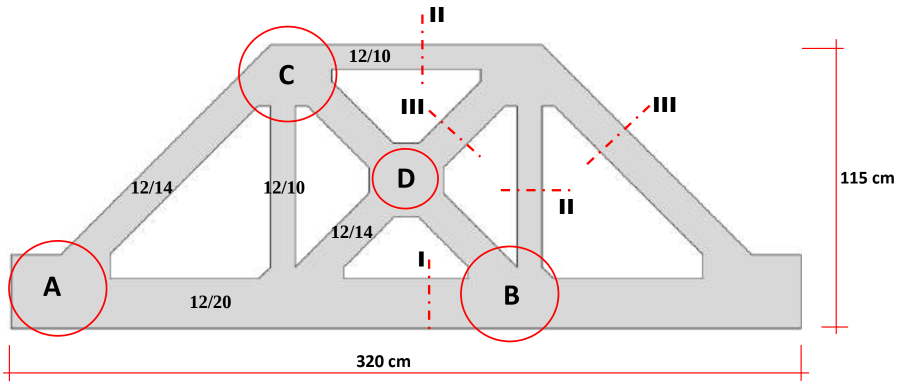


Figure 14. Details of the precast bridge frame [38].

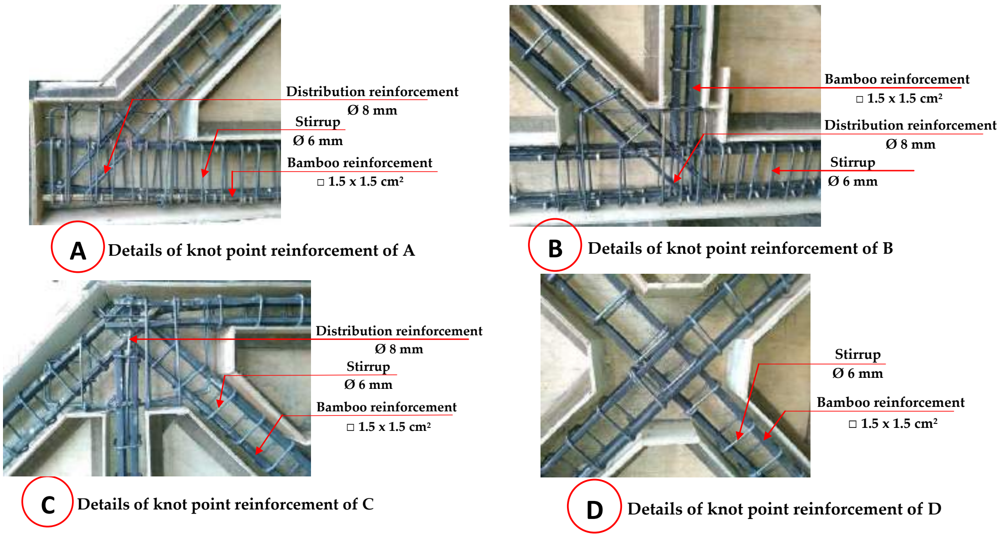
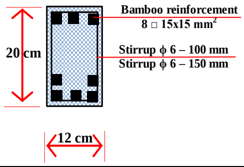
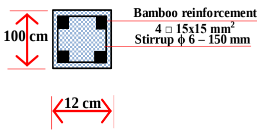
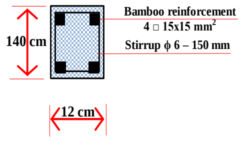


Figure 15. Details of the knot reinforcement for the bridge frames [38].

Table 4. Details of the bridge frame reinforcement [38].

Model	I (Shown in Figure 14)	II (Shown in Figure 14)	III (Shown in Figure 14)
Rigid portal model or "frame model"			

Testing of the precast bridges with the bamboo reinforced concrete frames was carried out directly with a load of a minibus-type vehicle. The load was given in stages and levels, starting from a zero load, Brio carload without passengers, Brio carload full of passengers, and Avanza carload full of passengers, as shown in Figure 16. The stage of reading the response variable was carried out when the axle of the car was at the coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm, and 300 cm from the support, as shown in Figure 17. Tests were carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, four LVDTs (Linear Variable Displacement Transducers) were installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, six pieces of LVDTs were installed, two pieces of LVDTs were installed in the middle of the side frame span, and four LVDTs were installed on the side of the four ends of the beam. The performance test settings for the precast bridges of the bamboo reinforced concrete frames are described in Figure 18.

The weights of the Brio and Avanza cars were calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight was based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

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Table 5. Specifications and weight of the minibus car.

Type of Car	Length	Height	Width	Wheelbase	Empty Weight or One Driver	Passenger Capacity	Weight with Full Passenger
	mm	mm	mm	mm	kg	persons	kg
Brio	3800	1485	1680	2655	930–965	5	1280
Avanza	4190	1695	1660	2655	1045–1095	7	1550

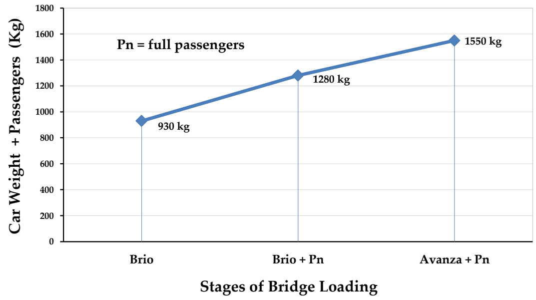

Figure 16. Loading stage of the precast bridges with a bamboo reinforced concrete frame.

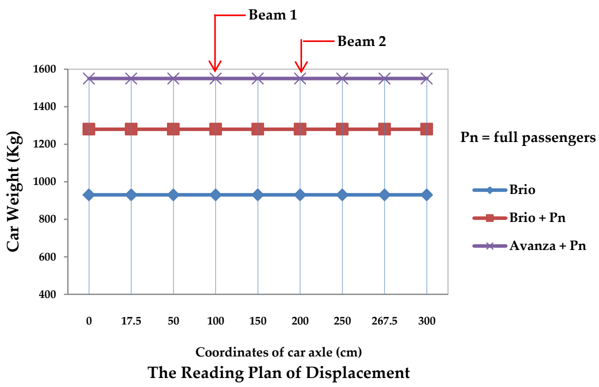

Figure 17. The coordinates of the reading points of the displacement and deformation.

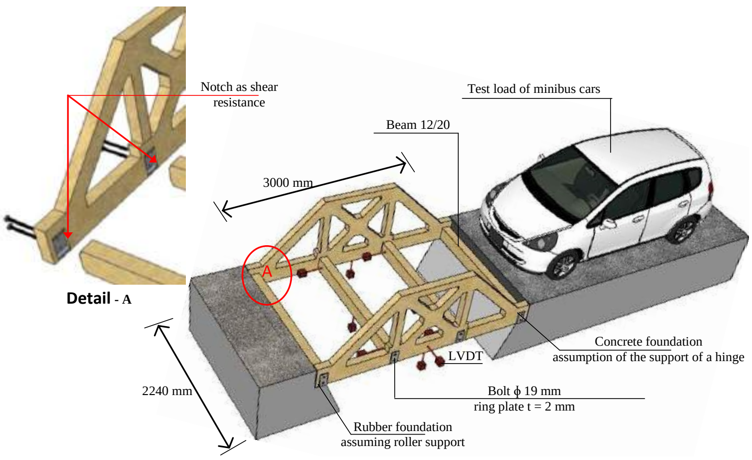

Figure 18. Arrangement of the testing of the bamboo reinforced concrete frame precast bridges.

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers, including Hidalgo (1992) in Sattar (1995) [46], Ghavami (2005) [1], Rong (2007) [47], and Lima Jr et al. (2008) [14]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [46] reported that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that, after testing, the bamboo reinforced concrete beams were left in the open air at the PUC Rio Brazil university campus; the bamboo reinforcements from the treated beams showed that the bond with the concrete was still in satisfactory condition after 15 years. Rong (2007) [47], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, stated that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement as the level of durability is good. Lima Jr et al. (2008) [14] experimented on the *Dendrocalamus giganteus* bamboo species, showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength or Young's Modulus. This is an important factor in the material for use as concrete reinforcement.

2.3. The Numerical Method Used

Determining the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis was written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack was done by using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo reinforced concrete is shown in Equations (1) and (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (E). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom, as shown in Figure 19. The stress–strain relationship for the field stress problem has the form of an equation, such as Equation (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \tag{1}$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \tag{2}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{4}$$

where E is the modulus of elasticity and ν is the Poisson's ratio. The principal stresses in two dimensions are calculated by Equation (4). The Fortran PowerStation 4.0 programming language for triangle elements is shown at the following link: https://bit.ly/3l1oU0d.

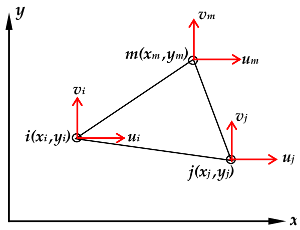

Figure 19. The degrees of freedom of the triangular element.

3. Results

Specifications for precast bridges of the bamboo reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car full of passengers. The test was carried out after several stages of work were done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, and completing or finishing the bridge. Recording of the test results started when the front axle of the minibus car was right on the hinge support and ended when the rear axle of the minibus car was right on the support of the roller. The test result data are shown in Table 7.

The security measure during the test was to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the LVDT tool. Besides, the bridge was planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test was carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and the deformation that occurred was deflection and elastic deformation. The critical load (P_{cr}) or initial crack load was 2.1 tons and the maximum test load for the minibuses was 1.55 tons.

Figures 20–25 show the beam displacement and the bridge frame with the minibus Brio car, the Brio full of passengers, and the AVANZA full of passengers. The maximum displacement with the load of the Brio car occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for the beam displacement. While, the maximum displacement with a full passenger Brio car occurred when the position of the front axle was at coordinates 200 cm and the rear axle was at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for the beam displacement. The maximum displacement with a full passenger AVANZA car load occurred when the front axle position was outside the bridge coordinates, which was 115 cm from the roller support, and the rear axle was at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for the displacement beam.

Based on the AASHTO [48] and RSNI T-12-2004 standards [49], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo reinforced concrete frame bridge meets the requirements based on the AASHTO [48] and RSNI T-12-2004 standards [49].

Table 6. Geometry and specifications of the precast bridges with a bamboo reinforced concrete frame.

Bridge span:	3 m
Foundation:	River stone
Bridge support:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam:	- Dimensions of the bridge beam 12 × 20 cm², tensile reinforcement (ϱ) = 4.688% and compressive reinforcement (ϱ') = 1.875% - Hose-clamp d = ¾ attached to the end of the bamboo reinforcement instead of hooks. - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand
Connection type:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model:	Rigid portal model or "frame model"
Bridge slab:	- 10 cm thick slab + spandex t = 0.3 mm. - Slab reinforcement using bamboo 1.5 × 1.5 cm² with a distance of 10 cm
Displacement and deformation of permit:	Based on AASHTO [48] and RSNI T-12-2004 standards [49], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge with bamboo reinforced concrete frames.

Bridge Load	Displacement and Deformation						
	Frame 1		Frame 2		Beam 1		Beam 2
	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)	Deformation [2] (mm)	Displacement [1] (mm)
Brio 930 kg	0.2	0.03	0.04	0.04	0.06	0.01	0.14
Brio + Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza + Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of the vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured as the direction of the horizontal of the cross-section.

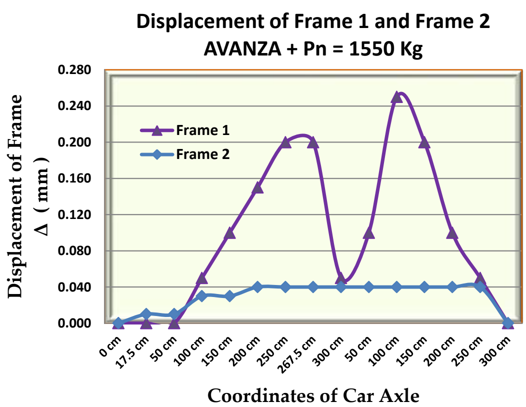

Figure 20. Displacement of the frame with loads of the Avanza car full of passengers.

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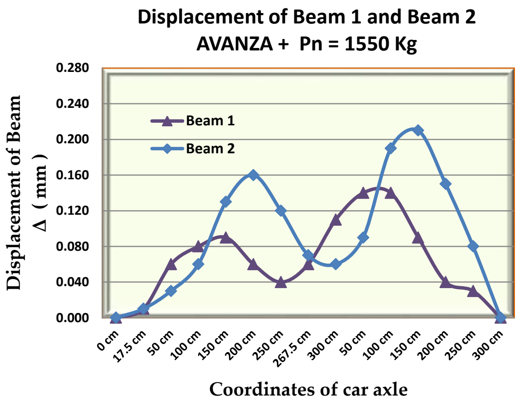

Figure 21. Displacement of the beam with loads of the Avanza car full of passengers.

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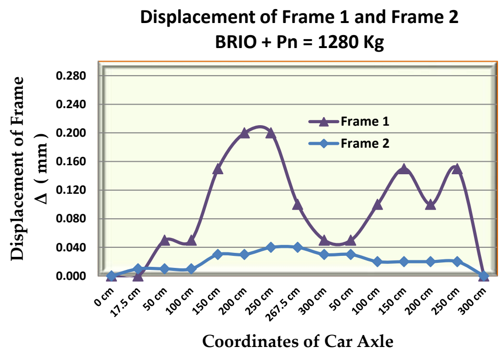

Figure 22. Displacement of the frame with loads of the BRIO car full of passengers.

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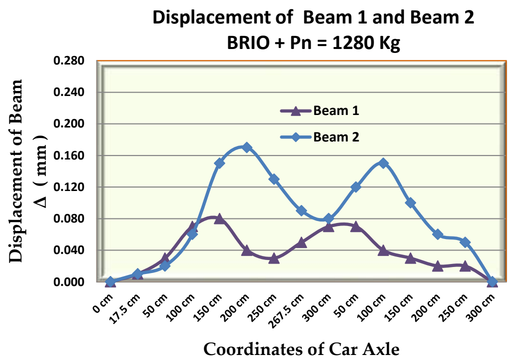

Figure 23. Displacement of the beam with loads of the BRIO car full of passengers.

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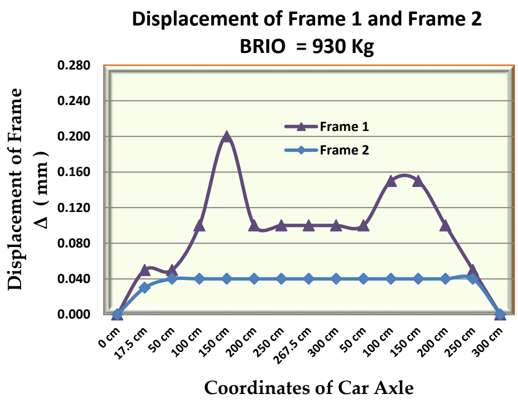

Figure 24. Displacement of the frame with loads of the BRIO car with no passengers.

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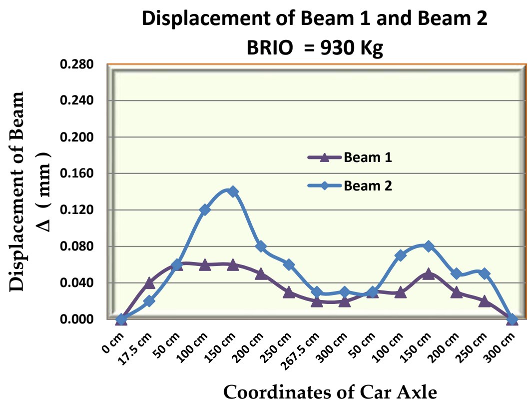

Figure 25. Displacement of the beam with loads of the BRIO car with no passengers.

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Figure 26 shows the deformation of the bridge beam of the bamboo reinforced concrete with a load of Brio minibuses, the Brio car full of passengers, and the Avanza car full of passengers. From Figure 26 and Table 7, we see that the maximum deformation occurs in the beam with the load of the Avanza car with a full passenger load, which is when the position of the front axle is outside the coordinates of the bridge, which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with the deformation of the beam being 0.20 mm.

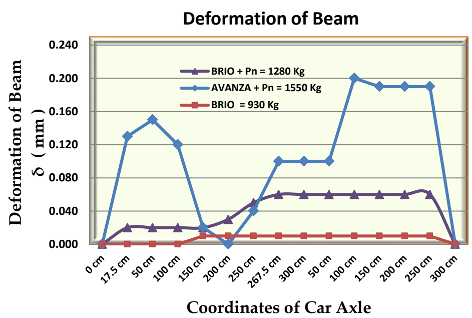

Figure 26. Deformation of the beam of the precast bridge of bamboo reinforced concrete.

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Figures 27–29 show the deformation of the bridge frame with the load of the Brio minibus, Brio car full of passengers, and the Avanza car full of passengers. The maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with a frame deformation of 0.04 mm.

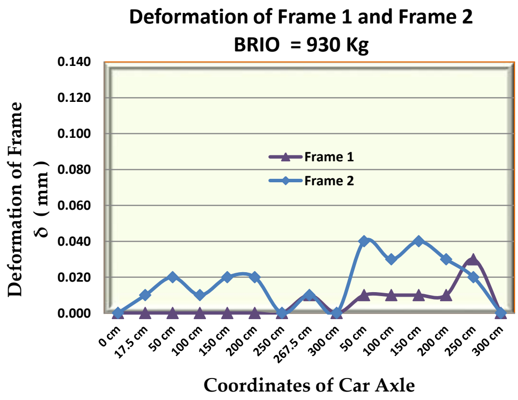

Figure 27. Deformation of the frame with loads of the Brio car with no passengers.

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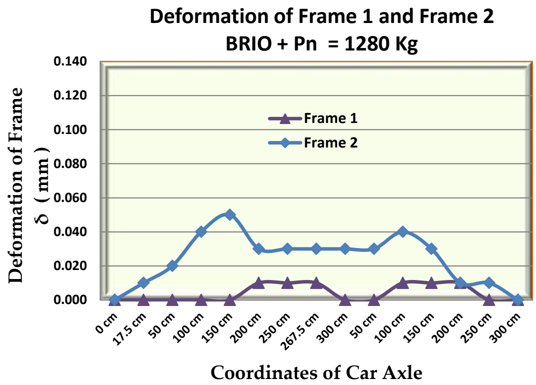

Figure 28. Deformation of the frame with loads of the Brio car full of passengers.

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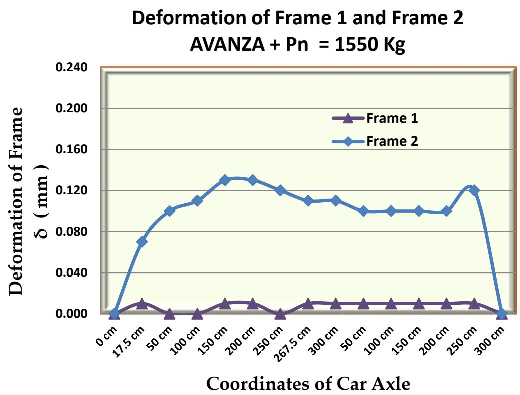

Figure 29. Deformation of the frame with loads of the Avanza car full of passengers.

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The maximum frame deformation with the load of the brio car full of passengers occurred when the position of the front axle was at coordinates 150 cm and the rear axle was at a distance of 85 cm from the hinge support, with a deformation of 0.05 mm. The maximum deformation of the frame with the load of the Avanza car full of passengers occurred when the position of the front axle was at the coordinates of the bridge of 150 cm, and the rear axle was at a distance of 115 cm from the hinge support, with a deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to a static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of the vehicle loads within the elastic limit measured in the horizontal direction of the cross section. Measurements were made by installing LVDTs (Linear Variable Displacement Transducers) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams, as shown in Figure 30.

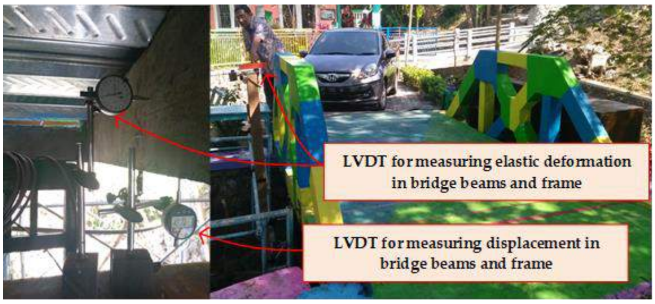

Figure 30. Measuring the elastic displacement and deformation.

The accuracy of the deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site, such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce the deformation and increase the deflection of the bridge beams. Figures 21 and 26 at the 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at the coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle; that is, the deformation continues to increase, respectively, at the front car axle and rear car axle. However, the accuracy of the deformation measurements needs attention as to the many determinants of accuracy that exist.

Figures 27 and 28 shows that the minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span or at the 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate; as shown in Figure 27, the coordinates at 250 cm convey inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [48] and RSNI T-12-2004 standards [49], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo reinforced concrete frame meet the requirements based on AASHTO [48] and RSNI T-12-2004 standards [49]. However, the relationship of load vs. displacement of the beam and the frame results from the field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and Surfer 9.8 software [50] based on laboratory test results. Simulations were carried out as control and validation of the experimental data. The bridge frame test simulation was carried out at the first crack load stage, which was 87 kN based on the frame loading capacity of only 100 kN. The discretization of the bamboo reinforced concrete bridge frame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figures 32 and 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [38], and with the field test results as shown in Figure 34. Figure 33 shows displacement in the X-direction; the green color shows the minimum displacement, and the orange and blue colors show the maximum positive and negative displacement, respectively. FEM analysis modeling on the bamboo reinforced concrete frames can be seen in Item 2.3 of the numerical method used.

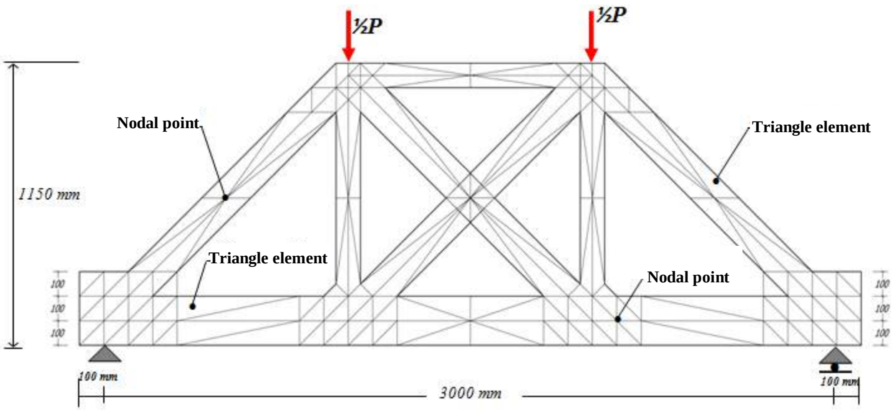

Figure 31. Discretization of the bamboo reinforced concrete bridge frames.

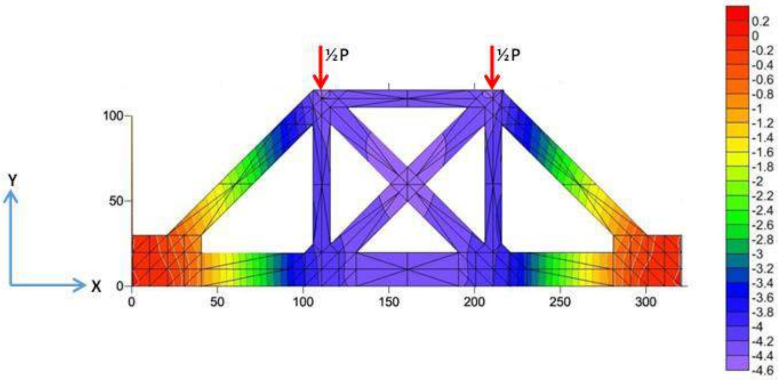

Figure 32. The displacement of Y-direction of the bridge frame.

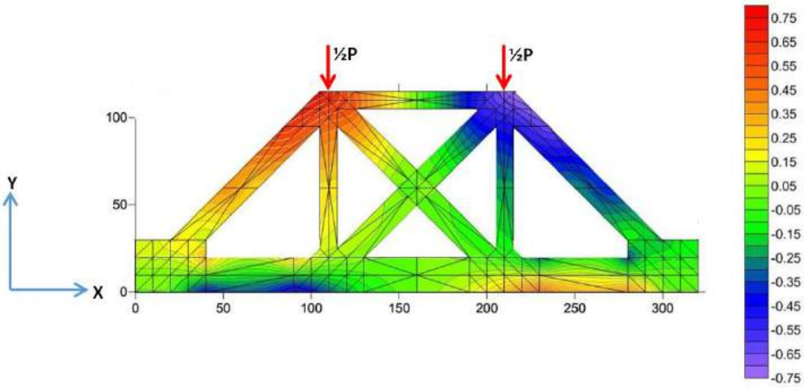

Figure 33. The displacement in the X-direction of the bridge frame.

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [24]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of the beams and bridge frames was analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [22,38], and the results of field experiments as shown in Figure 34. Control was carried out at the maximum load point of the bamboo reinforced concrete precast frame bridge test in the field, which was 15.5 kN, as shown in Figures 35 and 36. Documentation of the direct test of the bamboo reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of the aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, the SNI SNI-07-SE-2015 [51] dynamic analysis needed to be carried out for bridge types with a complex behavior, one of which was the main span exceeding 200 m. In this study, the bridge width is 2.24 m and the bridge span is 3.20 m, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements of AASHTO [48] and RSNI T-12-2004 [49], which is Δ_{max} = L/800 = 3.75 mm.

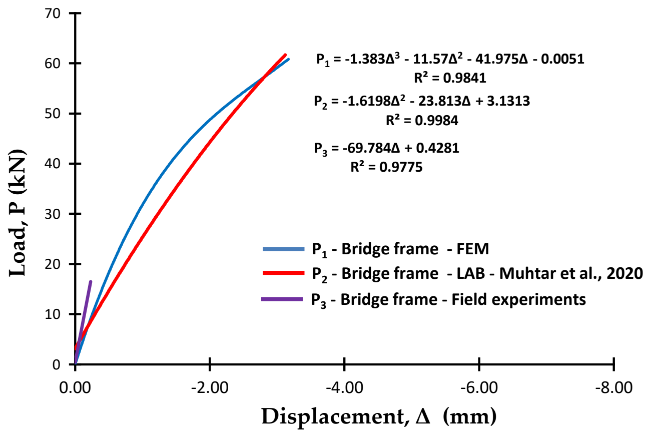

Figure 34. The relationship of load vs. displacement of the bridge frame.

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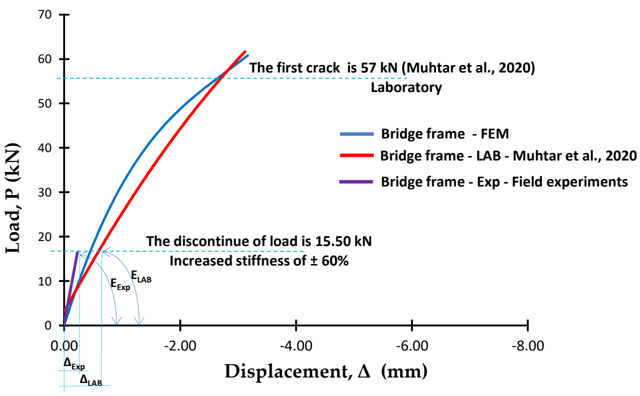

Figure 35. The relationship of load vs. displacement of the bridge frame from the laboratory test results, FEM results, and field experiment results.

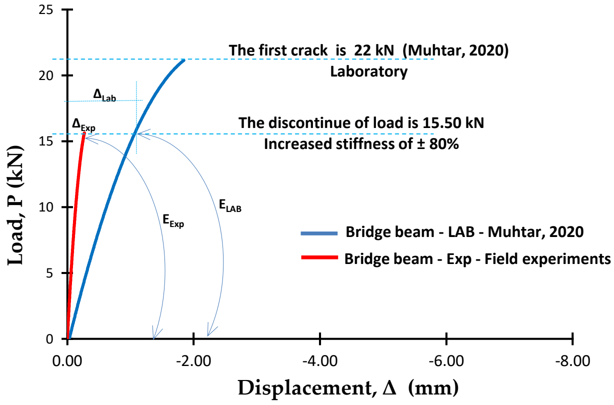

Figure 36. The relationship of load vs. displacement of the bridge beam from the laboratory test results and field experiment results.

The next step was validating the stiffness of the beam and bridge trusses. The main principle is that the bridge must be in a service condition, with a Serviceability Limit State (SLS) load. The elements of the bridge structure should not be subjected to cracks, deflection, or vibrations causing user discomfort. The allowable deflections are those that are elastic deflection and do not cause the crack. Stiffness is the main parameter of structural resistance. Therefore, the stiffness of the field test results needs to be validated by the stiffness of the laboratory test results. Load–displacement relationship diagrams of the experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results, and the displacement of the field experiments results of the bamboo reinforced concrete frame precast bridge at a stop load of 15.50 kN, the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame and 4.07 for the bridge beam. Figures 35 and 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of the laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs

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when the rear wheel is at the center of the span at the 150 cm coordinates and the front wheel is at the 415.5 cm coordinates (the front wheel is outside the bridge). While, the maximum displacement of the frame occurs when the rear wheel is at the 100 cm coordinates and the front wheel is at the 365.5 cm coordinates (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam; this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely, the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo reinforced concrete frame bridges have sufficiently good integrity; that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load of P = 15.5 kN, the stiffness of the bridge beam increased ±80% during the bridge test when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ±60% during the bridge test when compared to the frame stiffness of the laboratory results.

Author Contributions: The following statements should be used "conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflicts of Interest: The author declares no conflict of interest.

Comment [M31]: There is no co-author. The author is the first author and the corresponding author. I hope this "Author Contributions" item is removed

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September 30, 2020

Dear,

Michelle Wu
Assistant Editor
Applied Sciences Journal

I hereby submit my revised article in the Journal of Applied Sciences - Special Issue "Advanced Technologies in Wood Science". My article data is:

Title	:	Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia.
Corresponding Author	:	Muhtar, Department of Civil Engineering, Faculty of Engineering, University of Muhammadiyah Jember, Jember, 68121, Indonesia. E-mail: muhtar@unmuhjember.ac.id

I hope my submission can go through the review process and published as specified in the Author Information for **Applied Sciences** Journal.

Sincerely,

Muhtar

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October 6, 2020

Dear,

Ms. Jamie Li, M.Sc.
Co-Managing Editor & Associate Publisher

Applied Sciences Journal

I hereby submit my revised article (2nd revision) in the Journal of Applied Sciences - Special Issue "Advanced Technologies in Wood Science". My article data is:

Title	:	Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia.
Manuscript ID	:	applsci-931322
Corresponding Author	:	Muhtar, Department of Civil Engineering, Faculty of Engineering, University of Muhammadiyah Jember, Jember, 68121, Indonesia. E-mail: muhtar@unmuhjember.ac.id

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Muhtar

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Article

Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Received: date; Accepted: date; Published: date

Abstract: Bamboo is an inexpensive building material, environmentally friendly, and renewable that thrives in Indonesia. Bamboo has high tensile strength but has weaknesses, namely, it is easy to attack by insects and high water absorption. Utilization of bamboo as precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge are made with a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames are connected by four bridge beams. Bridge plate made of 10 cm thick concrete plate. The bridge support of reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficient good integrity, that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [Wikipedia]. Bamboo is a renewable building material such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboos such as tensile strength, flexural strength, and other mechanical properties can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3 - 4 years [6]. Also, bamboo is very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures such as warehouses, bridges, village traditional houses, and handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ± 1500 species of bamboo [2]. In terms of its potential, in 2000 the total area of bamboo plants in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and 1,414,000 ha of bamboo plant areas outside forest areas [27]. Arsad, E (2015) [27] revealed that in Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [46]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the type of petung bamboo (*Dendrocalamus asper*) and the type of ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with high tensile strength. The use of bamboo as concrete reinforcement for simple construction and is applied specifically to underdeveloped village areas that have a lot of bamboo.

Bamboo for concrete reinforcement because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the pull stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. However, bamboo also has weaknesses, which are easy to attack by insects and high water absorption. This study did not test for fungal and insect attack, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [42] and Stebbings (1904) [45], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aims to remove starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength, however after drying it undergoes a transition from a brittle behavior to a very resilient behavior [28]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [44] the content of bamboo fiber (BF) which is treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength.

In this study, the technology used to prevent decay and absorption, and the effect of high pH, is to provide Sikadur adhesive which is also a waterproof layer, and the basis is previous research that has been conducted by several researchers including (1) Ghavami (2005) [1] researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel, (2) Agarwal et al. (2014) [5] researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sicadur 32 Gel. From the sticky strength test, it was found that the best adhesive was Sicadur 32 Gel, (3) Lima Jr et al. (2008) [29] experimented on the Dendrocalamus giganteus bamboo species showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength and Young Modulus, (3) Javadian et al. (2016) [30] did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of high pH on strength properties will be carried out in future studies.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include: (1) Ghavami (2005) [1] concluded that bamboo can be used as a structural concrete element including beams, windows, frames, and elements that experience bending stress, (2) Agarwal et al. (2014) [5] conducted tests of treated bamboo reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements, (3) Sakaray et al. (2012) [31] conducted a feasibility test for moso type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete, (4) Nayak et al. (2013) [32] conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is 3 times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement, (5) Kaware et al. (2013) [33] reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel, (6) Khan (2014) [34] researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo reinforced concrete can be used successfully for structural and non-structural elements in building construction, (7) Rahman et al. (2011) [6] conducted tests on bamboo reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete, (8) Sethia & Baradiya (2014) [35] in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams, and (9) Terai & Minami (2011) [36] conducted a study on 11 bamboo reinforced concrete blocks and tested them to check for flexural cracks and shear cracks. And concluded that the crack pattern of bamboo reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel reinforced concrete beams.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [3-4], drying in free air [5-6], applying a waterproof layer [7], and sprinkled sand to modify the roughness of bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [8], Sikadur 32 Gel [5,1], Sikadur®-752 [4,7,9-12]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond-stress of bamboo reinforcement [4]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [13-16], bamboo as column reinforcement [17-19], bamboo as slab reinforcement, or panels reinforcement [20-22], and bamboo as a bridge frame reinforcement [23,24].

Muhtar [12] tested the flexural of 4 types of bridge beams with different treatments. The size of the bridge beam is 120 mm x 200 mm x 2100 mm with the area of tensile reinforcement ρ = 4.68% and compressive reinforcement ρ' = 1.88%. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose-clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of bamboo reinforcement with adhesive, sand, and hose-clamp can increase bond-stress and capacity of the bamboo reinforced concrete beam (BRC beam) [12]. The relationship between load vs. displacement is shown in Figure 1.

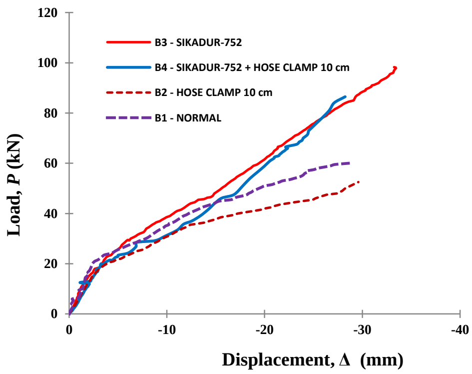


Figure 1. The relationship of Load vs. deflection of BRC beam [12]

Testing of bridge trusses has been carried out by several researchers including bamboo as reinforcement for truss easel [24] and as reinforcement for bridge frame with a span of 3 meters [23]. Dewi and Wonlele [24] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength, however, the collapse pattern still shows a bending effect [24].

Muhtar et al. [23] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of load (P) vs. deflection (Δ) of the two bridge frames is shown in Figure 2.

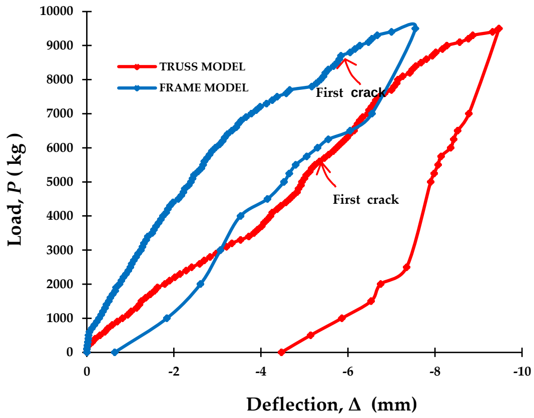


Figure 2. The relationship pattern of load vs. deflection of the bridge frame [23]

The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [12]. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [23]. The basis for using the results of previous laboratory research to control the results of direct tests in the field. The novelty that is expected: (1) obtaining a prototype of the precast concrete reinforced concrete bridge, and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. While the expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement which is applied to a simple frame bridge structure in underdeveloped village areas with local materials, cheap, environmentally friendly, and acceptable.

The targets of this research application are underdeveloped villages and lots of bamboos. Bamboo is a new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used is the petung bamboo (*Dendrocalamus asper*) aged 3-5 years [4,5]. Petung bamboo, the bamboo shoots are purplish black, covered with hairs such as brown velvet to blackish. Petung bamboo is large, segment length 40-50 cm, diameter 12-18 cm, with a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, Brink M (2008) in Wikipedia Indonesia (2016) [42]. The mechanical properties of petung bamboo are shown in Table 1. Tensile test for bamboo petung based on ASTM D 143-94 [37].

Table 1. Mechanical properties of petung bamboo

Mechanical properties	
Tensile strength (MPa)	105±8
Modulus of elasticity (GPa)	26±5
Elongation of fault (%)	16±1
Flexural strength (MPa)	153±11
Hardness (VHN)	5±1
Impact strength (J/mm2)	0.15±0.7

The bamboo part that is taken is 6-7 meters from the base of the bamboo stem. Bamboo is cut and split into bamboo reinforcement with a size of 15 x 15 mm^2. Bamboo to be used must be treated with the following steps: (a) bamboo is cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm x 15 mm x 2000 mm for bridge beam reinforcement, 15 mm x 15 mm x 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm x 15 mm x 1100 mm, the top stem is 15 mm x 15 mm x 1100 mm, and the diagonal stem is 15 mm x 15 mm x 1300 mm, (b) bamboo is soaked in water for 1 - 2 months to remove sugar content and prevent termites and insects [45], (c) dry in free air until the moisture content is approximately 12%, (d) the bamboo reinforcement is trimmed with a grinding machine according to the specified size, (e) providing a waterproof layer to reduce the occurrence of the hydrolysis process between bamboo and concrete, (f) sand sprinkling to modify the roughness of bamboo reinforcement.

Ghavami (2005) [1] and Agarwal et al. (2014) [5] concluded that the best waterproof layer is Sikadur 32 Gel. The waterproof or adhesive layer uses Sikadur®-752 produced PT Sika Indonesia [3,10]. Sikadur®-752 is A solvent-free, 2-component super-low viscosity-liquid, based on high strength epoxy resins. Especially for injecting into cavities and cracks in concrete. Usually used to fill and seal cavities and crack in structural concrete. Sikadur®-752 is applied to bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage.

Table 2. The specification of Sikadur®-752 [41]

Components	Properties
Colour	Yellowish
Density	Approx. 1.08 kg/L
Mixing Ratio, by weight/volume	2 : 1
Pot life at +30°C	35 min
Compressive strength	62 N/mm² at 7 days (ASTM D-695) 64 N/mm² at 28 days
Tensile strength	40 N/mm² at 28 days (ASTM D-790)
Tensile Adhesion Strength	2 N/mm² (Concrete failure, over echanically prepared concrete surface)
Coefficient of Thermal Expansion	-20 °C to +40 °C 89 x 10-6 per °C
Modulus of elasticity	1060 N/mm²

Table 3. The mix composition of concrete

The concrete mix design	Cement (PPC)	Fine Aggregate	Coarse Aggregate	Water
	Kg/m³			
Material per-m³	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

The hose-clamp used is diameter ¾" made in Taiwan [3,12]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm diameter with f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of bamboo (E_b) was 17236 MPa with a tensile strength of 127 N/mm² [3] and the modulus of steel elasticity (E_s) was 207736 MPa [3]. The concrete mixture used is Portland Pozzolana Cement (PPC) with a pH of 7, sand, coarse aggregate, and water with a mixed proportion of 1.81: 2.82: 0.52 as shown in Table 3. The average compressive strength of concrete is 31.31 MPa at the age of 28 days. The process of treating bamboo to assembling the bamboo reinforcement can be seen in Figures 3-8.

Figure 3. Take bamboo from the soaking

Figure 4. Drying bamboo in free air

Figure 5. Tidy up the bamboo according to size

Figure 6. Gives a waterproof coating

Figure 7. Sand sprinkling on bamboo reinforcement

Figure 8. Stringing bamboo reinforcement

196 *2.2. Methods*

The dimensions of the bridge are made with a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge is made 280 cm. Two bridge frames are connected by four bridge beams. Each end of the bridge beam is connected to the knot point with 2 bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of joints between the beam and precast bridge frame are shown in Figures 10-11. The bridge supports are made of reinforced concrete with the assumption of hinge support and a rubber bearing assuming roller support. While the bridge plate is made of 10 cm thick concrete plate with 0.3 mm thick spandex. The shape and model of the precast bridge of the bamboo reinforced concrete frame are described in Figure 12. Details of the reinforcement of the precast bridge beams are shown in Figure 13. Details of the reinforcement of the bridge frame are shown in Figures 14-15 and Table 4.

The design concept of bamboo reinforced concrete beams follows Ghavami (2005) and Muhtar (2020) as shown in Figure 9. The balance of the concrete compressive force (C = Cb '+ Cc) and the tensile force (T) must be met as shown in Figure 9. The tensile strength of bamboo reinforcement (T) is obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo reinforced concrete beams due to the breaking of the bonds between bamboo and concrete.

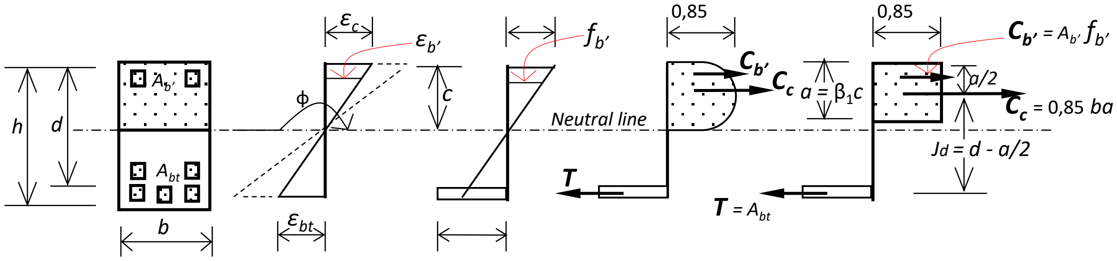


Figure 9. Stress-strain distribution diagram in a BRC beam

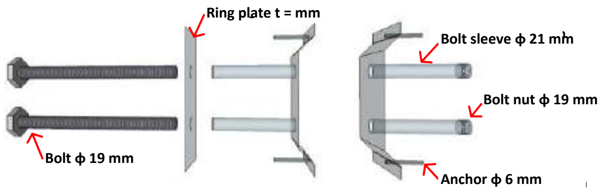
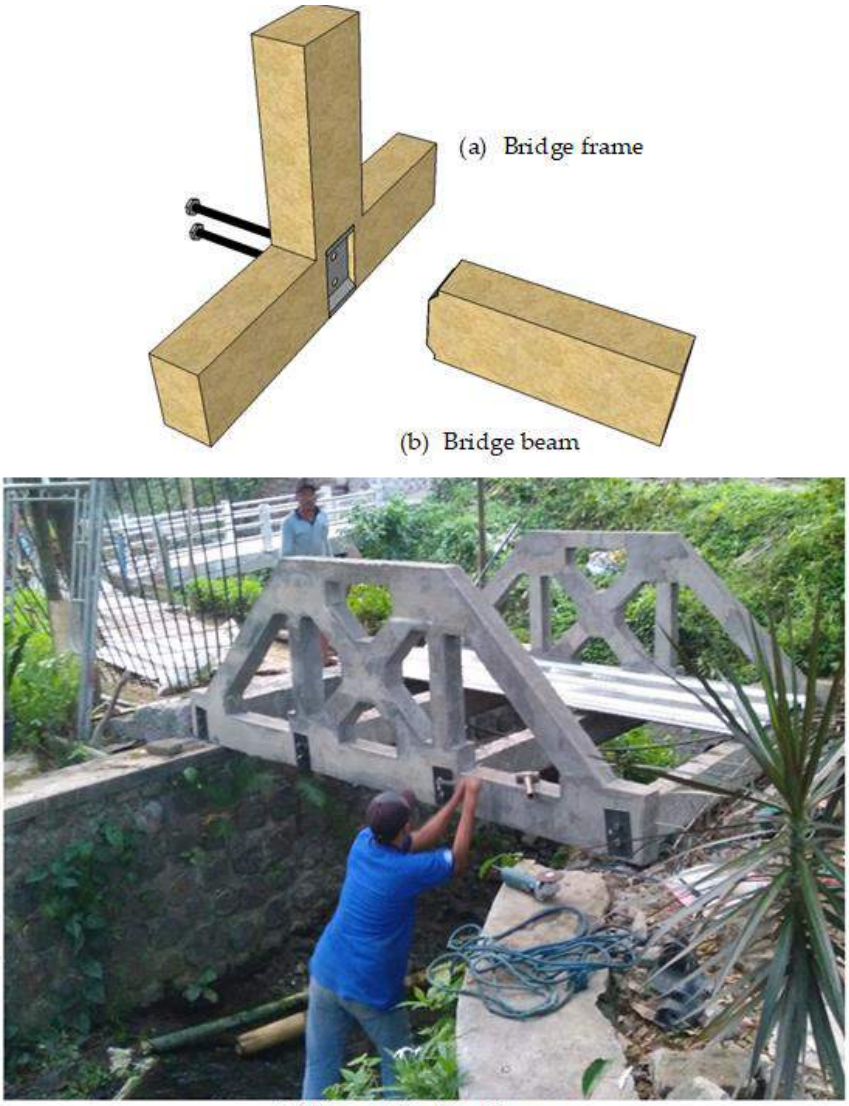


Figure 10. Details of ring plate and bolt sleeve



(c) Precast bridge frames

Figure 11. Models and applications of precast connections

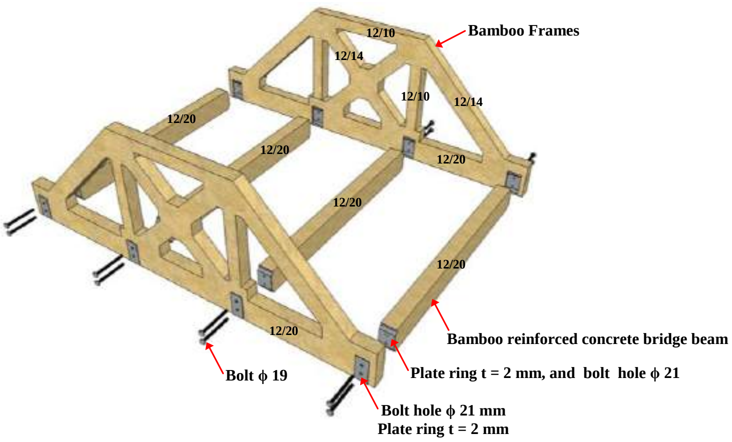


Figure 12. Model of the precast bridge from bamboo reinforced concrete

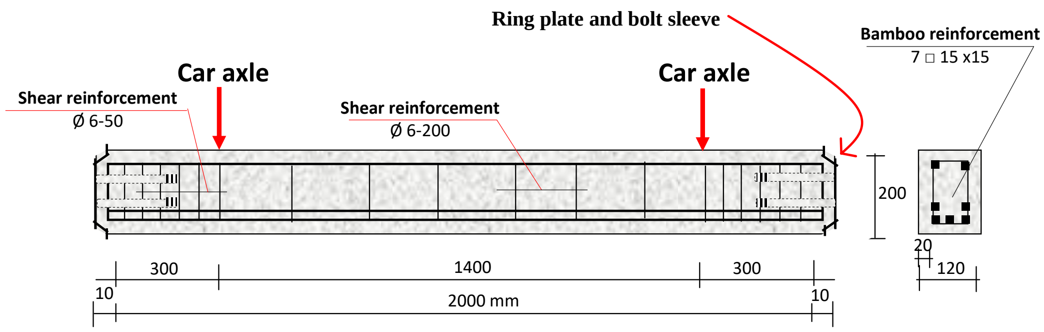


Figure 13. Details of Precast bridge beam reinforcement [12]

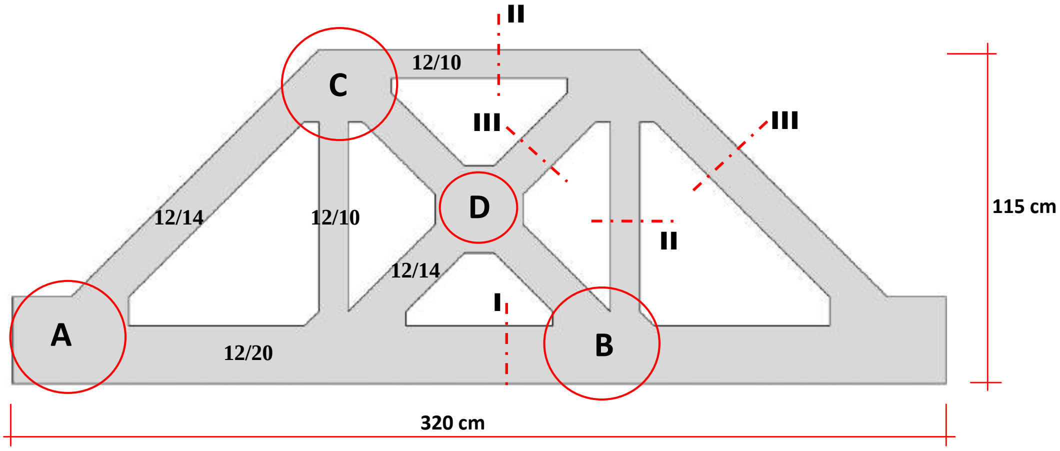


Figure 14. Details of precast bridge frame [23]

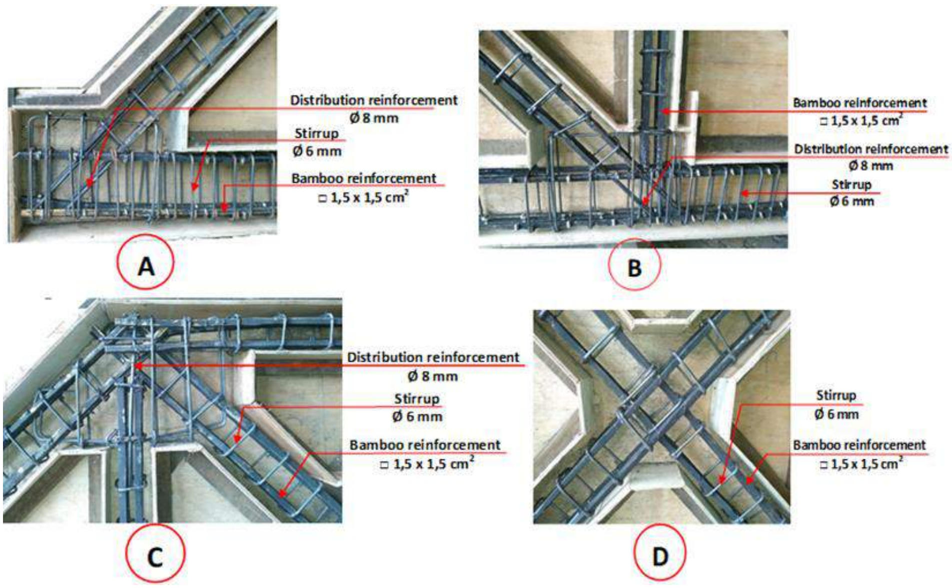
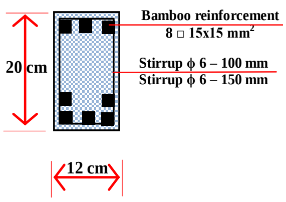
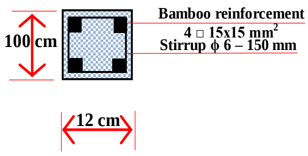
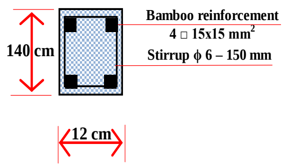


Figure 15. Details of knot reinforcement for bridge frames [23]

Table 4. Details of bridge frame reinforcement [23]

Model	I (Shown in Figure 14)	II (Shown in Figure 14)	III (Shown in Figure 14)
Rigid portal model or "frame model"	 Bamboo reinforcement 8 □ 15x15 mm²; Stirrup ϕ 6 – 100 mm; Stirrup ϕ 6 – 150 mm; 20 cm; 12 cm	 Bamboo reinforcement 4 □ 15x15 mm²; Stirrup ϕ 6 – 150 mm; 100 cm; 12 cm	 Bamboo reinforcement 4 □ 15x15 mm²; Stirrup ϕ 6 – 150 mm; 140 cm; 12 cm

Testing of precast bridges with bamboo reinforced concrete frames is carried out directly with a load of a minibus type vehicle. The load is given in stages and levels, starting from zero loads, Brio carload without passengers, Brio carload of full passenger, and AVANZA carload of the full passenger as shown in Figure 16. The stage of reading the response variable is carried out when the axle of the car is at coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm and 300 cm from the support as shown in Figure 17. Tests are carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, 4 LVDTs (Linear Variable Displacement Transducers) are installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, 6 pieces of LVDT were installed, 2 pieces of LVDT were installed in the middle of the side frame span, and 4 LVDTs were installed on the side of the four ends of the beam. The performance test settings for precast bridges of bamboo reinforced concrete frames are described in Figure 18.

The weight of the Brio car and the Avanza car is calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight is based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

Table 5. Specifications and weight of minibus car

Type of car	Length	Height	Width	Wheelbase	Empty weight or one driver	Passenger capacity	Weight with full passenger
	mm	mm	mm	mm	kg	person	kg
Brio	3800	1485	1680	2655	930 - 965	5	1280
Avanza	4190	1695	1660	2655	1045 - 1095	7	1550

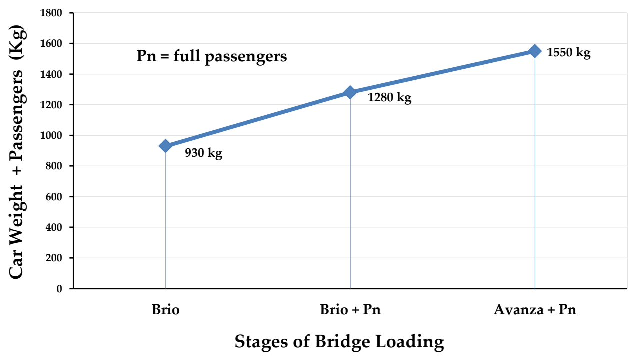


Figure 16. Loading stage of precast bridges of bamboo reinforced concrete frame

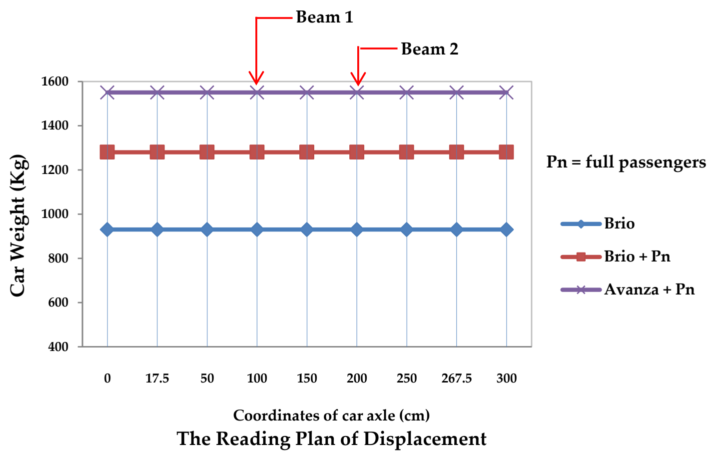


Figure 17. The coordinates of the reading points of displacement and deformation

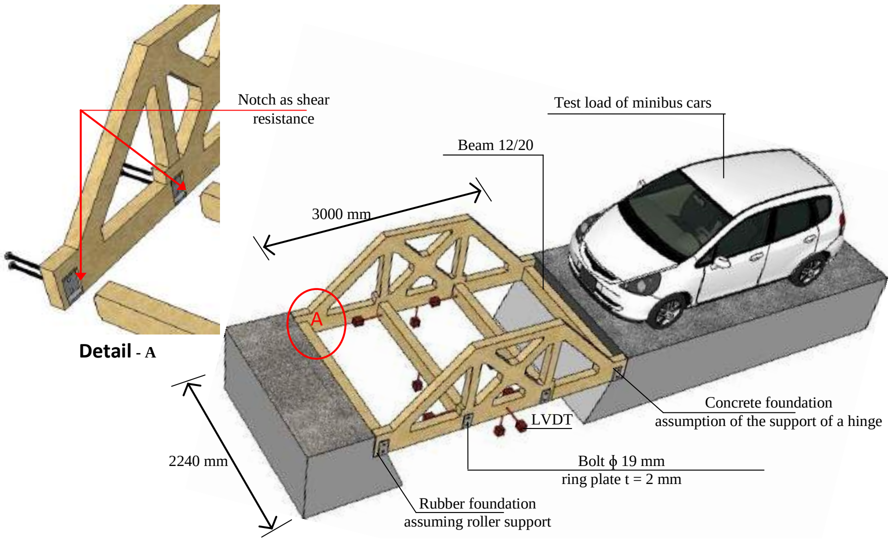


Figure 18. Arrangement of testing for bamboo reinforced concrete frame precast bridges

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers including Hidalgo (1992) in Sattar (1995) [43], Ghavami (2005) [1], Rong BS (2007) [40], Lima Jr et al. (2008) [29]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [43] reports that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that after testing, bamboo reinforced concrete beams are left in the open air at the PUC Rio Brasil university campus, bamboo reinforcements from treated beams show that the bond with the concrete is still in satisfactory condition after 15 years. B.S. Rong (2007) [40], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, states that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement with the level of durability is good. Lima Jr et al. (2008) [29] experimented on the Dendrocalamus giganteus bamboo species showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength and Young Modulus. This is an important factor of the material for use as concrete reinforcement.

2.3. The numerical method used

To determine the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis is written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo reinforced concrete is shown in Eq. (1) and Eq. (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (E). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom as shown in Figure 19. The stress-strain relationship for the field stress problem has the form of an equation such as Eq. (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \tag{1}$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \tag{2}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{4}$$

where E is the modulus of elasticity and ν is the Poisson's ratio. And the principal stresses in two dimensions are calculated by Eq. (4).

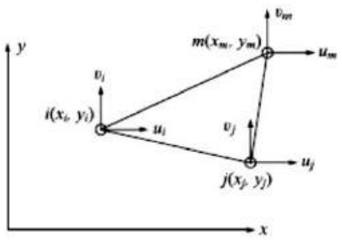


Figure 19. The degrees of freedom of triangular element

3. Results

Specifications for precast bridges of the bamboo reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car of the full passenger. The test is carried out after several stages of work are done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, completing or finishing the bridge. Recording of test results response starts when the front axle of the minibus car is right on the hinge support and ends until the rear axle of the minibus car is right on the support of the roller. The test result data is shown in Table 7.

The security measure during the test is to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the LVDT tool. Besides, the bridge is planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test is carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and deformation that occurs is deflection and elastic deformation. The critical load (Pcr) or initial crack load is 2.1 tons and the maximum test load for minibusses is 1.55 tons.

Figures 20-25 show the beam displacement and the bridge frame with the minibus Brio car, Brio with full passengers, and AVANZA with full passengers. The maximum displacement with the load of the Brio car occurs when the position of the front axle is at coordinates 150 cm and the rear axle is at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for beam displacement. While the maximum displacement with a full passenger Brio car occurs when the position of the front axle is at coordinates 200 cm and the rear axle is at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for beam displacement. For maximum displacement with a full passenger AVANZA car load occurs when the front axle position is outside the bridge coordinates, which is 115 cm from the roller support, and the rear axle is at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for displacement beam.

Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo reinforced concrete frame bridge meets the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25].

Table 6. Geometry and specifications of precast bridges bamboo reinforced concrete frame

Bridge span	:	3 meters
Foundation	:	River stone
Bridge support	:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam	:	- Dimensions of the bridge beam 12 x 20 cm^2, tensile reinforcement (ϱ) = 4.688% and compressive reinforcement (ϱ') = 1.875% - Hose-clamp d = ¾ ″attached to the end of the bamboo reinforcement instead of hooks. - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand
Connection type	:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model	:	Rigid portal model or "frame model"
Bridge slab	:	- 10 cm thick slab + spandex t = 0.3 mm. - Slab reinforcement using bamboo 1.5 x 1.5 cm2 with a distance of 10 cm
Displacement/deformation of permit	:	Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge of bamboo reinforced concrete frames

Bridge load	**Displacement and deformation**						
	Frame 1		**Frame 2**		**Beam 1**		**Beam 2**
	Displacement[1] (mm)	**Deformation[2] (mm)**	**Displacement[1] (mm)**	**Deformation[2] (mm)**	**Displacement[1] (mm)**	**Deformation[2] (mm)**	**Displacement[1] (mm)**
Brio 930 kg	0.2	0.03	0.04	0.04	0.06	0.01	0.14
Brio+Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza+Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of vehicle loads within the elastic limit measured in the direction of horizontal of the cross-section

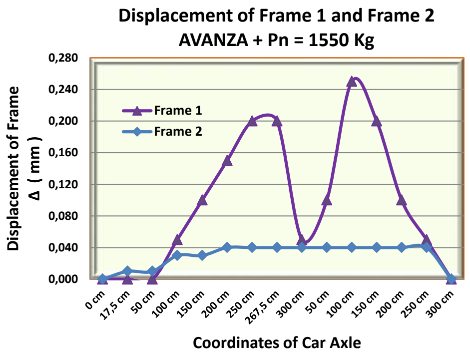


Figure 20. Displacement of the frame with loads of AVANZA car of full passengers

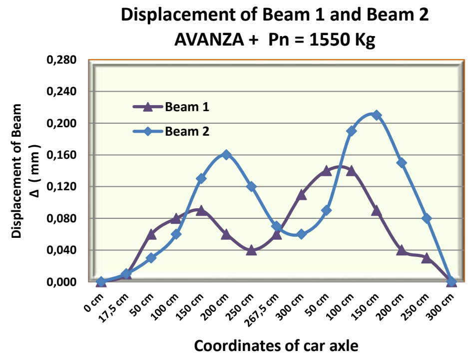


Figure 21. Displacement of the beam with loads of AVANZA car of full passengers

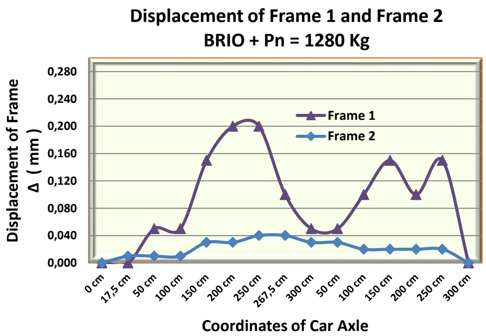


Figure 22. Displacement of the frame with loads of BRIO car of full passengers

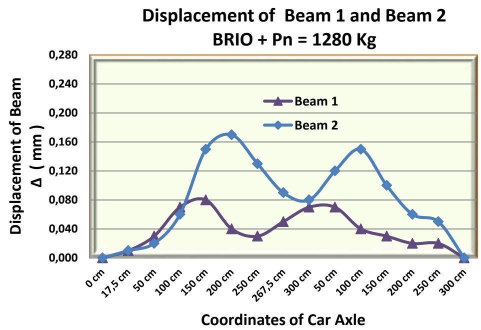


Figure 23. Displacement of the beam with loads of BRIO car of full passengers

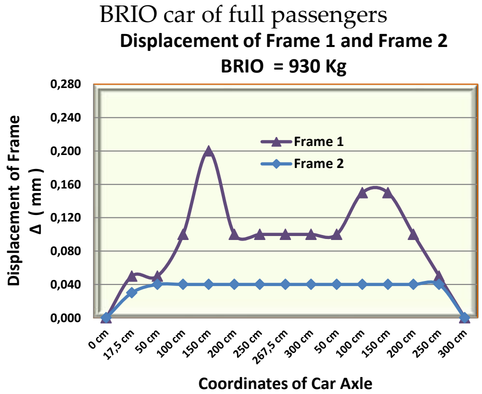


Figure 24. Displacement of the frame with loads of BRIO car of no passengers

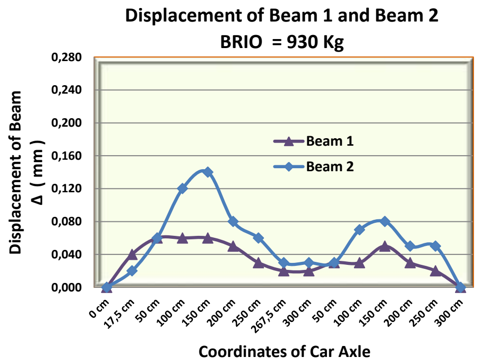


Figure 25. Displacement of the beam with loads of BRIO car of no passengers

Figure 26 shows the deformation of the bridge beam of bamboo reinforced concrete with a load of Brio minibusses car, Brio car with full passengers, and AVANZA car with full passengers. From Figure 26 and Table 7, it shows that the maximum deformation occurs in the beam with the load of the AVANZA car with a full passenger, which is when the position of the front axle is outside the coordinates of the bridge which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with deformation a beam of 0.20 mm.

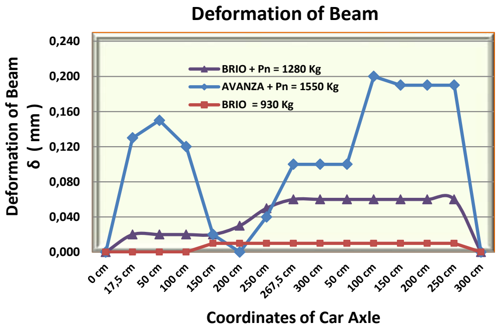


Figure 26. Deformation of the beam of the precast bridge of bamboo reinforced concrete

Figures 27-29 show that the deformation of the bridge frame with the load of the Brio minibus, Brio car with full passengers, and AVANZA car with full passengers. Maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with frame deformation of 0.04 mm.

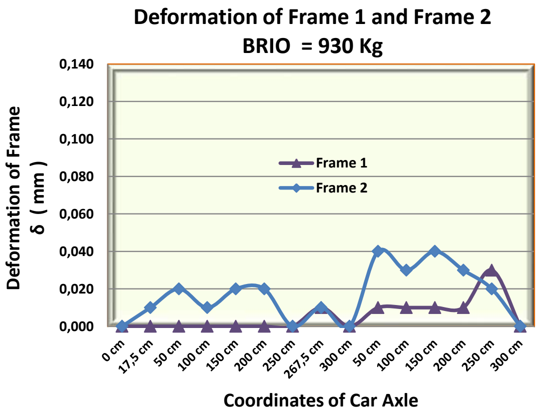


Figure 27. Deformation of the frame with loads of BRIO car of no passengers

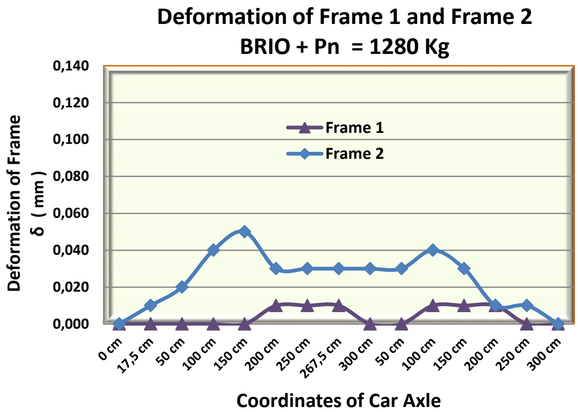


Figure 28. Deformation of the frame with loads of BRIO car of full passengers

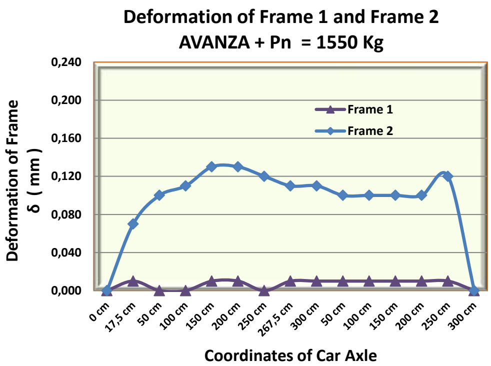


Figure 29. Deformation of the frame with loads of AVANZA car of full passengers

While the maximum frame deformation with the load of the brio car with full passengers occurs when the position of the front axle is at coordinates 150 cm and the rear axle is at a distance of 85 cm from the hinge support, with deformation of 0.05 mm. For the maximum deformation of the frame with the load of the AVANZA car with full passengers occurs when the position of the front axle is at the coordinates of the bridge is 150 cm, and the rear axle is at a distance of 115 cm from the hinge support with deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of vehicle loads within the elastic limit measured in the horizontal direction of the cross-section. Measurements were made by installing LVDT (Linear Variable Displacement Transducers) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams as shown in Figure 30.

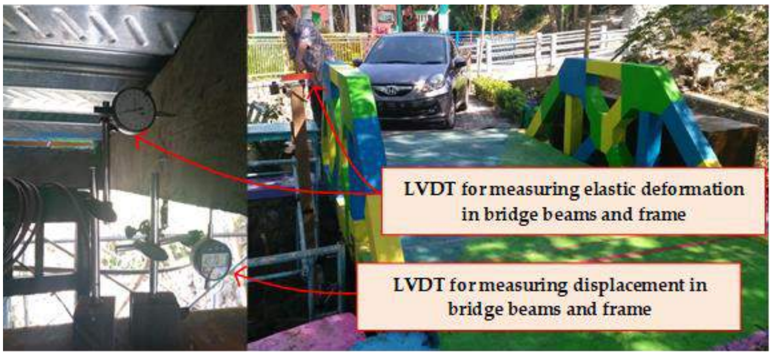


Figure 30. The measuring elastic displacement and deformation

The accuracy of deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam, this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce deformation and increase the deflection of the bridge beams. Figure 26 and Figure 21 at 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle, that is, the deformation continues to increase, respectively, of the front car axle and rear car axle. However, the accuracy of deformation measurements really needs attention to many determinants of accuracy.

Figure 27 and Figure 28 shows that minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is the middle of the bridge span or at 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate, as shown in Figure 27 the coordinates of 250 cm occur inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [38] and RSNI T-12-2004 standards [25], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo reinforced concrete frame meet the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25]. However, the relationship of load vs. displacement of beam and frame results from field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and surfer 9.8 software [26] based on laboratory test results. Simulations were carried out as control and validation of experimental data. The bridge frame test simulation is carried out at the first crack load stage, which is 87 kN based on the frame loading capacity of only 100 kN. The discretization of the Bamboo Reinforced Concrete Bridge Frame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figure 32 and Figure 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [23] and field test results as shown in Figure 34. Figure 33 shows displacement in the x-direction, green color shows minimum displacement, orange, and blue color shows the maximum positive and negative displacement. FEM analysis modeling on the bamboo reinforced concrete frames can be seen in item 2.3 the numerical method used.

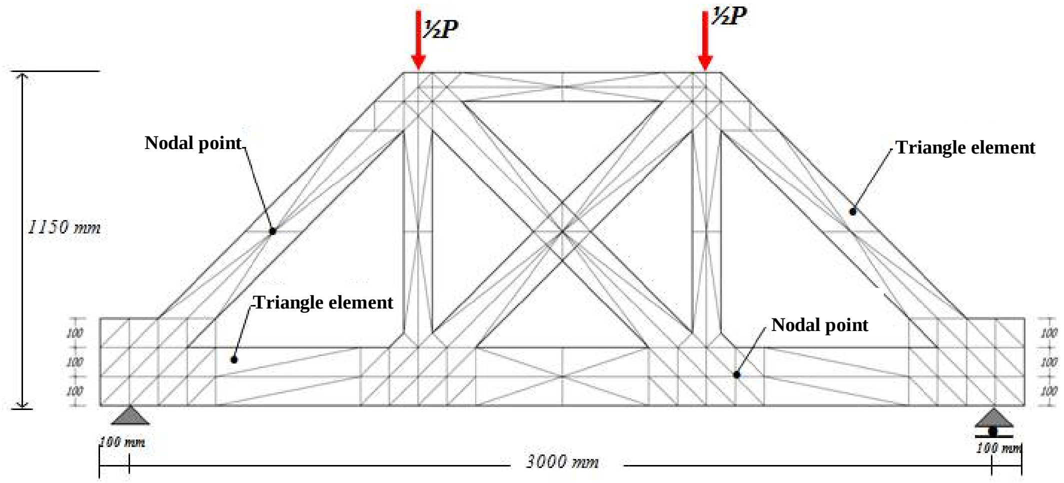


Figure 31. Discretization of Bamboo Reinforced Concrete Bridge Frames

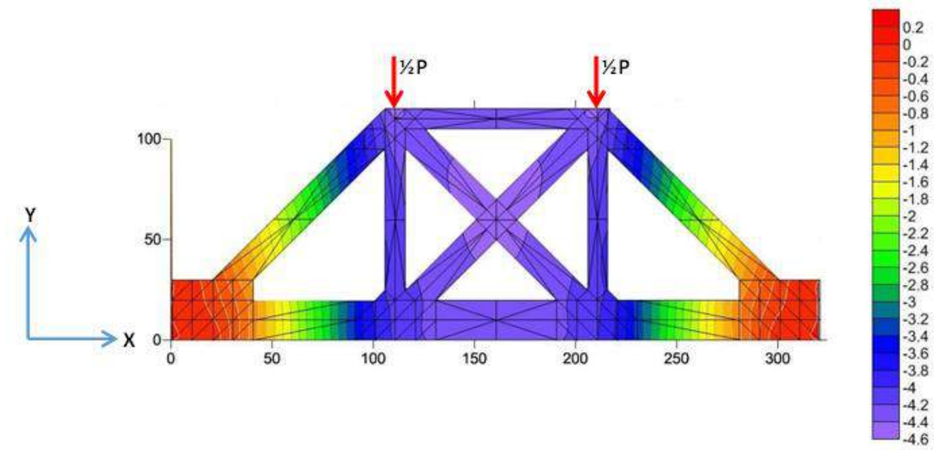


Figure 32. The displacement of Y-direction of the bridge frame

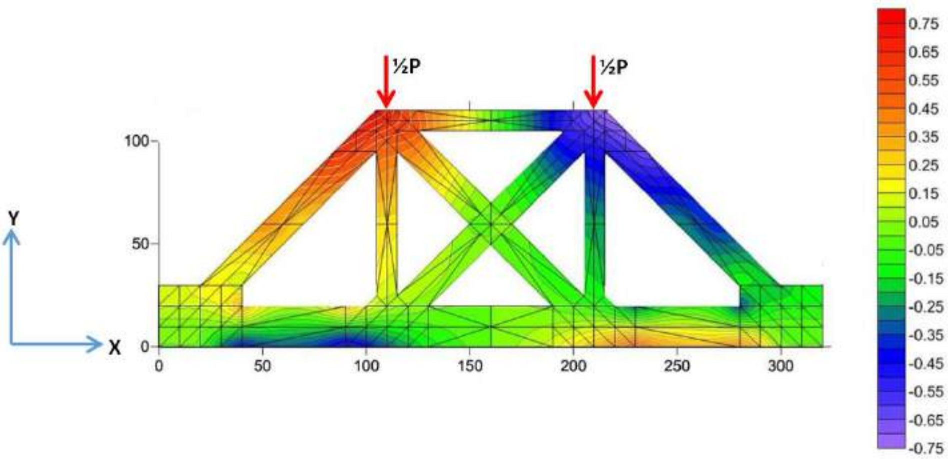


Figure 33. The displacement of X-direction of the bridge frame

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [7]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of beams and bridge frames is analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [12,23], and the results of field experiments as shown in Figure 34. Control is carried out at the maximum load point of the bamboo reinforced concrete precast frame bridge test in the field, which is 15.5 kN as shown in Figure 35 and Figure 36. Documentation of the direct test of bamboo reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, SNI SNI-07-SE-2015 [39] dynamic analysis needs to be carried out for bridge types with complex behavior, one of which is the main span exceeding 200 meters. In this study, the bridge width is 2.24 meters and the bridge span is 3.20 meters, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements. AASHTO [38] and RSNI T-12-2004 [25] that is Δ_{max} = L/800 = 3.75 mm.

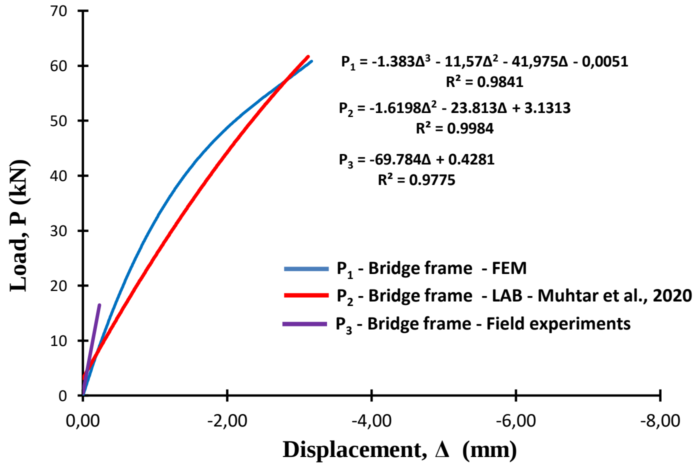


Figure 34. The relationship of load vs. displacement of the bridge frame

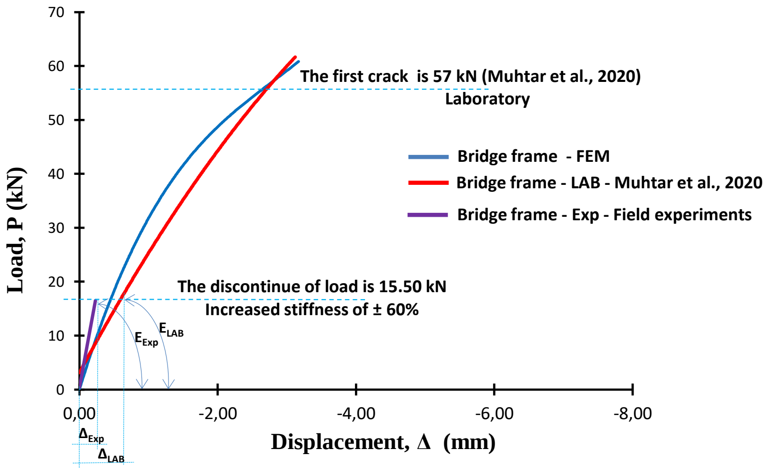


Figure 35. The relationship of load vs. displacement of bridge frame from laboratory test results, FEM results, and field experiment results

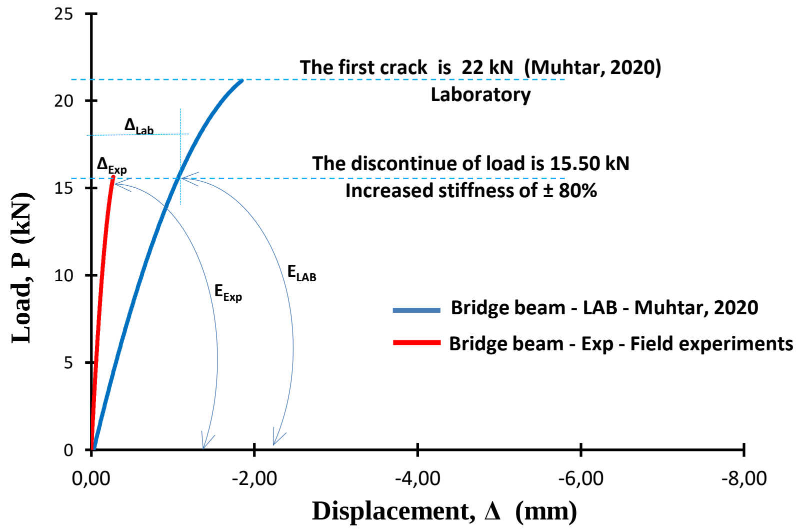


Figure 36. The relationship of load vs. displacement of bridge beam from laboratory test results and field experiment results

The next step is validating the stiffness of the beam and bridge trusses. Load-displacement relationship diagrams of experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results and the displacement of the field experiments results of the bamboo reinforced concrete frame precast bridge at a stop load of 15.50 kN, obtained the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame, and 4.07 for the bridge beam. Figure 35 and Figure 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs when the rear wheel is at the center of the span of 150 cm coordinates and the front wheel is at 415.5 cm coordinates (the front wheel is outside the bridge). While the maximum displacement of the frame occurs when the rear wheel is at coordinates 100 cm and the front wheel is at coordinates 365.5 cm (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam, this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo reinforced concrete frame bridges have sufficiently good integrity, that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load P = 15.5 kN, the stiffness of the bridge beam increased ± 80% during the bridge test, when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ± 60% during the bridge test, when compared to the frame stiffness of the Laboratory results.

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Conflicts of Interest: The authors declare no conflict of interest.

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Precast Bridges of Bamboo Reinforced Concrete in Disadvantaged Village Areas in Indonesia

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Abstract: Bamboo is an inexpensive building material, environmentally friendly, and renewable that thrives in Indonesia. Bamboo has high tensile strength but has weaknesses, namely, it is easy to attack by insects and high water absorption. Utilization of bamboo as precast concrete bridge reinforcement must be treated first through soaking, drying, and giving a waterproof coating and sand. This research aimed to obtain a precast bamboo reinforced concrete bridge technology with good integrity, with measuring parameters of deformation and deflection according to AASHTO standards. The dimensions of the bridge are made with a span of 320 cm, a width of 224 cm, and a height of 115 cm. Two bridge frames are connected by four bridge beams. Bridge plate made of 10 cm thick concrete plate. The bridge support of reinforced concrete is assumed to be the hinge support and the rubber bearing is assumed to be the roller support. The bamboo reinforced concrete frame bridge test was carried out directly with a load of a minibus type vehicle. The test results show that the precast bamboo reinforced concrete frame bridges have sufficient good integrity, that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement occurs in the bridge frame of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

Keywords: precast bridges; bamboo reinforced concrete (BRC); bridge technology; bridge frame

1. Introduction

The continued use of industrial products has caused permanent pollution. Permanent pollution is environmental pollution caused by industrial waste without recycling or the continuous use of raw materials from nature without renewal. The use of bamboo as a renewable building material can reduce pollution and maintain a healthy environment [1]. Bamboo is a grass plant with cavities and nodes in its stems [42]. Bamboo is a renewable building material such as wood. Bamboo has the advantage of being economical, growing fast, and does not take long to achieve mechanical resistance. Mechanical resistance of bamboo such as tensile strength, flexural strength, and other mechanical properties can be achieved in a relatively fast time, namely at the age of bamboo ranging from 3 - 4 years [6]. Also, bamboo is very abundant in tropical and subtropical areas around the world [1]. Indonesia is a country with a tropical climate. One of the plants that can thrive in Indonesia is bamboo. Bamboo is scattered throughout Indonesia. Bamboo has been widely used as a material for simple structures such as warehouses, bridges, village traditional houses, and handicrafts for rural communities. In Indonesia, there are more than 100 species of bamboo. Around the world, there are ± 1500 species of bamboo [2]. In terms of its potential, in 2000 the total area of bamboo plants in Indonesia was 2,104,000 ha, consisting of 690,000 ha of bamboo planted in forest areas and 1,414,000 ha of bamboo plant areas outside forest areas [27]. Arsad, E (2015) [27] revealed that in Hulu Sungai Selatan Regency, the bamboo area was estimated to be around 22,158 ha with a production of about 3000 stems/ha. The description of the potential for bamboo production in East Java is 29,950,000 stems/year, Yogyakarta 2,900,000 stems/year, Central Java 24,730,000 stems/year, and West Java 14,130,000 stems/year [46]. With such a large production potential, efforts must be made to increase its economic value, including being used as an alternative to concrete reinforcement. The best bamboos that are widely used as structural elements are the type of petung bamboo (*Dendrocalamus asper*) and the type of ori bamboo (*Bambusa blumeana*), because these two bamboos have the best technical specifications with high tensile strength. The use of bamboo as concrete reinforcement for simple construction and is applied specifically to underdeveloped village areas that have a lot of bamboo.

Bamboo for concrete reinforcement because it has a relatively high tensile strength. The tensile strength of bamboo can reach 370 MPa in its outer fibers [1]. The failure of the elements of the bridge frame or roof truss usually occurs in the tensile stem elements. Bamboo has a high enough tensile strength suitable for use in tensile elements. Bamboo is suitable for use in tensile elements simple construction such as roof truss, simple bridge trusses, simple house construction elements, and so on. Muhtar et al. (2018) [11] test the pull-out of bamboo reinforcement with a layer of Sikadur®-752 and hose clamps embedded in a concrete cylinder showed an increase in tensile stress of up to 240% compared to untreated bamboo reinforced concrete. A single reinforced BRC beam with a bamboo reinforcing area ratio of 4% exceeds the ultimate load of steel-reinforced SRC beam by 38.54% with a steel reinforcement area ratio of 0.89% [3]. However, bamboo also has weaknesses, which are easy to attack by insects and high water absorption. This study did not test for fungal and insect attack, but the technology to prevent fungus and insect attack was based on the opinion and research of Ridley (1911) [42] and Stebbings (1904) [45], namely that soaking in water for two months is sufficient to prevent insect attack. Soaking and drying aim to remove starch or sugar content in bamboo. The criterion for sufficient soaking is that the bamboo smells bad. The soaking causes the bamboo's water content to increase and decrease its strength, however after drying it undergoes a transition from a brittle behavior to a very resilient behavior [28]. The effect of alkaline cement does not cause the bamboo to decrease in strength. According to Ming Li (2017) [44], the content of bamboo fiber (BF) which is treated with the right alkaline can effectively increase toughness, flexural strength, and tensile strength. Moe Thwe (2003) [51] conducted a study on the durability of bamboo with treatment using Calcium Hydroxide (CaOH2) to increase flexibility and durability.

In this study, the technology used to prevent decay and absorption, and the effect of high pH, is to provide Sikadur adhesive which is also a waterproof layer, and the basis is previous research that has been conducted by several researchers including (1) Ghavami (2005) [1] researched the attachment of bamboo reinforcement with several adhesives applied to the pull-out test and beam test. From the results of his research concluded that the best adhesive is Sicadur 32 Gel, (2) Agarwal et al. (2014) [5] researched bamboo reinforcement treated with Araldite adhesive, Tepecrete P-151, Anti Corr RC, and Sicadur 32 Gel. From the sticky strength test, it was found that the best adhesive was Sicadur 32 Gel, (3) Lima Jr et al. (2008) [29] experimented on the Dendrocalamus giganteus bamboo species showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not reduce its tensile strength and Young Modulus, (3) Javadian et al. (2016) [30] did research on several types of epoxy coatings to determine the bonding behavior between concrete and bamboo-composite reinforcement. The results showed that the bamboo-composite reinforcement without bonding layers was adequate with the concrete matrix, but with an epoxy base layer and sand particles, it could provide extra protection without losing bond strength. However, tests for decay resistance, absorption, and the effect of high pH on strength properties will be carried out in future studies, (4) Muhtar et al. (2019) [3] processing bamboo reinforcement by immersing in water for 1 month, coating with Sikadur®-752, and applying a hose clamp. The pull-out test results show that the bond-stress increases by 200% when compared to untreated bamboo. Sikadur®-752 adhesive is quite effective in preventing the occurrence of hygroscopic and hydrolysis processes between bamboo and concrete. The non-adhesive hose-clamp does not affect bond-stress.

Several researchers who have concluded that bamboo is suitable for use as concrete reinforcement include: (1) Ghavami (2005) [1] concluded that bamboo can be used as a structural concrete element including beams, windows, frames, and elements that experience bending stress, (2) Agarwal et al. (2014) [5] conducted tests of treated bamboo reinforced columns and beams and concluded that all tests indicated that bamboo has the potential to replace steel as reinforcing beam and column elements, (3) Sakaray et al. (2012) [31] conducted a feasibility test for moso type bamboo as a reinforcing material for concrete and the conclusion was that bamboo could be used as a substitute for steel in concrete, (4) Nayak et al. (2013) [32] conducted a study to analyze the effect of replacing steel reinforcement with bamboo reinforcement. One of the conclusions wrote that bamboo reinforcement is 3 times cheaper than steel reinforcement and that the engineering technique is cheaper than steel reinforcement, (5) Kaware et al. (2013) [33] reviewed bamboo as a reinforcing material for concrete and one conclusion was that bamboo exhibits ductile behavior like steel, (6) Khan (2014) [34] researched bamboo as an alternative material to substitute for reinforcing steel and one of the results of his study revealed that bamboo reinforced concrete can be used successfully for structural and non-structural elements in building construction, (7) Rahman et al. (2011) [6] conducted tests on bamboo reinforced concrete beams and one of the conclusions wrote that bamboo is a potential reinforcing material in concrete, (8) Sethia & Baradiya (2014) [35] in one conclusion revealed that bamboo can be used as an alternative to steel reinforcement in beams, (9) Terai & Minami (2011) [36] conducted a study on 11 bamboo reinforced concrete beams and tested them to check for flexural cracks and shear cracks. And concluded that the crack pattern of bamboo reinforced concrete (BRC) beams resembles the fracture pattern of steel-reinforced concrete (RCC) beams so that the fracture behavior of bamboo reinforced concrete (BRC) beams can be evaluated with the existing formula on RCC steel reinforced concrete beams, and (10) Muhtar (2020) [12] conducted a flexural test on 4 beams with untreated bamboo reinforcement and treated with Sikadur®-752 and hose-clamp. The test results showed that the beam treated with Sikadur®-752 increased load capacity by 164% when compared to untreated reinforced bamboo. With the first treatment, bamboo is suitable for use as a simple construction concrete reinforcement.

Bamboo as a concrete reinforcement must be treated beforehand, such as immersion in water [3-4], drying in free air [5-6], applying a waterproof layer [7], and sprinkled sand to modify the roughness of bamboo reinforcement. Usage of the adhesive or waterproof coating can be done in various ways, such as paint [8], Sikadur 32 Gel [5,1], Sikadur®-752 [4,7,9-12]. Strengthening of bamboo reinforcement with adhesive or waterproof coating can increase the bond-stress of bamboo reinforcement [4]. Bamboo as reinforcement for concrete construction elements has been widely researched, including bamboo as beam reinforcement [13-16], bamboo as column reinforcement [17-19], bamboo as slab reinforcement, or panels reinforcement [20-22], and bamboo as a bridge frame reinforcement [23,24].

Muhtar [12] tested the flexural of 4 types of bridge beams with different treatments. The size of the bridge beam is 120 mm x 200 mm x 2100 mm with the area of tensile reinforcement ϱ = 4.68% and compressive reinforcement ϱ' = 1.88%. Strengthening of bamboo reinforcement is done by applying adhesive as a waterproof layer. Modification of the roughness of the bamboo reinforcement is done by sprinkled sand and installing hose-clamps on the tensile reinforcement. The test was carried out using the four-point load method. The position of the loading point is adjusted to the distance of the minibus car axle. The test results show that the bridge beam with bamboo reinforcement can reach the ultimate load of 98.3 kN with an initial crack load of 20 kN. Modification of the roughness of bamboo reinforcement with adhesive, sand, and hose-clamp can increase bond-stress and capacity of the bamboo reinforced concrete beam (BRC beam) [12]. The relationship between load vs. displacement is shown in Figure 1.

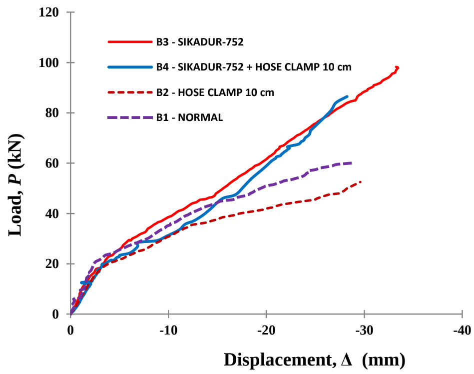


Figure 1. The relationship of Load vs. deflection of BRC beam [12]

Testing of bridge trusses has been carried out by several researchers including bamboo as reinforcement for truss easel [24] and as reinforcement for bridge frame with a span of 3 meters [23]. Dewi and Wonlele [24] concluded that the collapse of the frame structure was caused by a combination of compressive and shear forces at the positioning of support knot points. Failure at the knot placement causes the tensile and compressive rods to be unable to develop the maximum tensile and compressive strength, however, the collapse pattern still shows a bending effect [24].

Muhtar et al. [23] tested two bridge frame models, namely one frame with symmetry reinforcement as the joint frame model or "truss model", one frame with flexural reinforcement as the rigid portal model or "frame model". The test results show that the rigid portal model or "frame model" has higher rigidity and load capacity than the joint frame model or "truss model". The rigid portal model or "frame model" has an initial crack load capacity of 8700 kg or 87 kN and the joint frame model or "truss model" has an initial crack load capacity of 5500 kg or 55 kN. The relationship pattern of load (P) vs. deflection (Δ) of the two bridge frames is shown in Figure 2.

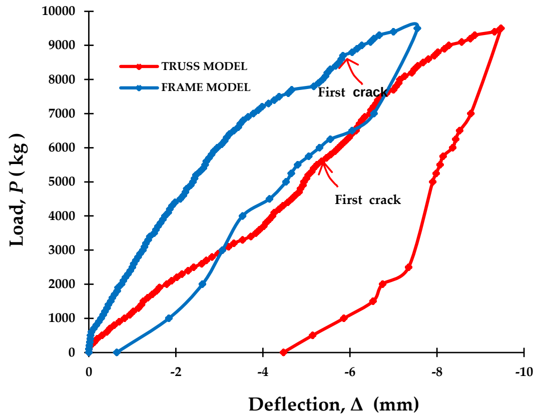


Figure 2. The relationship pattern of load vs. deflection of the bridge frame [23]

The dimensions and reinforcement of the bridge beams used in this study are the same as Muhtar's (2020) research [12]. In this study, strengthening of reinforcement with hose-clamp is only to tensile reinforcement, whereas in previous studies it was carried out on all reinforcement. The hose-clamps strengthening with the distance is too tightly together can reduce the elastic properties of the bamboo and reduce capacity. The bridge frame model used in this study is a rigid frame model or "frame model" as in the experiment conducted by Muhtar et al. (2020) [23]. The reinforcement model on the lower side frame stem is installed with the concept of flexural reinforcement, whereas in previous studies it was carried out with the concept of truss reinforcement or symmetry, and their behavior shows flexural behavior. The basis for using the results of previous laboratory research to control the results of direct tests in the field. The novelty that is expected: (1) obtaining a prototype of the precast concrete reinforced concrete bridge, and (2) increasing the stiffness and capacity of the precast bridge elements when assembled into a complete unit. While the expected benefits are that the research results can be used as the basis for the use of bamboo as a substitute for steel reinforcement which is applied to a simple frame bridge structure in underdeveloped village areas with local materials, cheap, environmentally friendly, and acceptable.

The targets of this research application are underdeveloped villages and lots of bamboos. Bamboo is new and renewable energy from natural resources that are very abundant in rural areas. Bamboo needs to be used, including reinforced concrete. The use of bamboo is one of the real efforts to increase the economic strength of the community. Based on previous research and the abundant potential of bamboo, it is necessary to use it as a reinforcing element for simple precast reinforced concrete bridges, especially in rural areas with lots of bamboos.

2. Materials and Methods

2.1. Materials

The bamboo used is the petung bamboo (*Dendrocalamus asper*) aged 3-5 years [4,5]. Petung bamboo, the bamboo shoots are purplish-black, covered with hairs such as brown velvet to blackish. Petung bamboo is large, segment length 40-50 cm, diameter 12-18 cm, with a stem height of up to 20 m. The nodes are surrounded by aerial roots. The wall thickness of the bamboo internode is between 11 and 36 mm, Brink M (2008) in Wikipedia Indonesia (2016) [42]. The mechanical properties of petung bamboo are shown in Table 1. Tensile test for bamboo petung based on ASTM D 143-94 [37].

Table 1. Mechanical properties of petung bamboo [47]

Mechanical properties	
Tensile strength (MPa)	105±8
Modulus of elasticity (GPa)	26±5
Elongation of fault (%)	16±1
Flexural strength (MPa)	153±11
Hardness (VHN)	5±1
Impact strength (J/mm^2)	0.15±0.7

The bamboo part that is taken is 6-7 meters from the base of the bamboo stem. Bamboo is cut and split into bamboo reinforcement with a size of 15 x 15 mm^2. Bamboo to be used must be treated with the following steps: (a) bamboo is cut and split close to the size of the bamboo reinforcement to be used, namely 15 mm x 15 mm x 2000 mm for bridge beam reinforcement, 15 mm x 15 mm x 3160 mm for the lower side truss bridge reinforcement. Meanwhile, the reinforcement for the vertical truss is 15 mm x 15 mm x 1100 mm, the top stem is 15 mm x 15 mm x 1100 mm, and the diagonal stem is 15 mm x 15 mm x 1300 mm, (b) bamboo is soaked in water for 1 - 2 months to remove sugar content and prevent termites and insects as shown in Figure 3 [45], (c) dry in free air until the moisture content is approximately 12% as shown in Figure 4, (d) the bamboo reinforcement is trimmed with a grinding machine according to the specified size as shown in Figure 5, (e) providing a waterproof layer to reduce the occurrence of the hydrolysis process between bamboo and concrete as shown in Figure 6, (f) sand sprinkling to modify the roughness of bamboo reinforcement as shown in Figure 7, and (g) Stringing bamboo reinforcement as shown in Figure 8.

Ghavami (2005) [1] and Agarwal et al. (2014) [5] concluded that the best waterproof layer is Sikadur 32 Gel. Muhtar (2019) [3] treated bamboo with Sikadur®-752 and hose-clamp. The test results show that the adhesion strength increases up to 200% and the beam capacity increases 164% when compared to untreated bamboo reinforcement. The waterproof or adhesive layer uses Sikadur®-752 produced PT Sika Indonesia [3,10]. Sikadur®-752 is A solvent-free, 2-component super-low viscosity-liquid, based on high strength epoxy resins. Especially for injecting into cavities and cracks in concrete. Usually used to fill and seal cavities and crack in structural concrete. Sikadur®-752 is applied to bamboo reinforcement to prevent water absorption. The effectiveness and durability of Sikadur®-752 adhesives require further research. The specifications of Sikadur®-752 are shown in Table 2. The coating was carried out in two stages. The second waterproof layer was applied to perfect the waterproof layer of the first stage. The thermal effect of Sikadur®-752 on bamboo reinforcement can be prevented by the moisture content of 12% in bamboo. In determining the strength of bamboo, 12% of moisture content in the air-dry condition has been considered as a reference standard [48] and the temperature does not significantly affect the loss of stiffness [49]. Chemical treatment of bamboo helps increase the durability of the bamboo fibers and reduces the moisture absorption of the bamboo fibers [50].

Table 2. The specification of Sikadur®-752 [41]

Components	Properties		
Colour	Yellowish		
Density	Approx. 1.08 kg/L		
Mixing Ratio, by weight/volume	2: 1		
Pot life at +30°C	35 min		
Compressive strength	62 N/mm²	at 7 days	(ASTM D-695)
	64 N/mm²	at 28 days	
Tensile strength	40 N/mm²	at 28 days	(ASTM D-790)
Tensile Adhesion Strength	2 N/mm² (Concrete failure, over mechanically prepared concrete surface)		
Coefficient of Thermal Expansion	-20 °C to +40 °C	89 x 10-6 per °C	
Modulus of elasticity	1060 N/mm²		

Table 3. The mix composition of concrete

The concrete mix design	**Cement (PPC)**	**Fine Aggregate**	**Coarse Aggregate**	**Water**
	Kg/m³			
Material per-m³	381	185	689	1077
Mix composition	1	1.81	2.82	0.52

The hose-clamp used is diameter ¾" made in Taiwan [3,12]. The shear reinforcement of the bridge beam and bridge frame uses steel of 6 mm diameter with f_y 240 MPa quality. From the results of the bamboo tensile test in this study, it was found that the modulus of elasticity of bamboo (E_b) was 17236 MPa with a tensile strength of 127 N/mm² [3] and the modulus of steel elasticity (E_s) was 207736 MPa [3]. The concrete mixture used is Portland Pozzolana Cement (PPC) with a pH of 7, sand, coarse aggregate, and water with a mixed proportion of 1.81: 2.82: 0.52 as shown in Table 3. The average compressive strength of concrete is 31.31 MPa at the age of 28 days. The process of treating bamboo to assembling the bamboo reinforcement can be seen in Figures 3-8.

Figure 3. Take bamboo from the soaking

Figure 4. Drying bamboo in free air

Figure 5. Tidy up the bamboo according to size

Figure 6. Gives a waterproof coating

Figure 7. Sand sprinkling on bamboo reinforcement

Figure 8. Stringing bamboo reinforcement

2.2. Methods

The dimensions of the bridge are made with a span of 320 cm, a width of 224 m, and a frame height of 115 cm. The clean span of the inside of the bridge is made 280 cm. Two bridge frames are connected by four bridge beams. Each end of the bridge beam is connected to the knot point with 2 bolts and a steel ring plate with a thickness of 2 mm to prevent stress concentration. Details and models of joints between the beam and precast bridge frame are shown in Figures 10-11. The bridge supports are made of reinforced concrete with the assumption of hinge support and a rubber bearing assuming roller support. While the bridge plate is made of 10 cm thick concrete plate with 0.3 mm thick spandex. The shape and model of the precast bridge of the bamboo reinforced concrete frame are described in Figure 12. Details of the reinforcement of the precast bridge beams are shown in Figure 13. Details of the reinforcement of the bridge frame are shown in Figures 14-15 and Table 4.

The design concept of bamboo reinforced concrete beams follows Ghavami (2005) [1] and Muhtar (2020) [12] as shown in Figure 9. The balance of the concrete compressive force (C = Cb '+ Cc) and the tensile force (T) must be met as shown in Figure 9. The tensile strength of bamboo reinforcement (T) is obtained by multiplying the bond stress with the shear area in the bamboo reinforcement. The failure of the bamboo reinforced concrete beams due to the breaking of the bonds between bamboo and concrete.

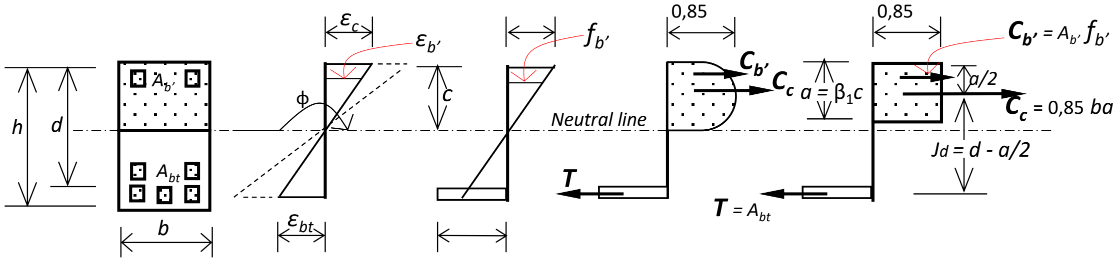


Figure 9. Stress-strain distribution diagram in a BRC beam [1,12]

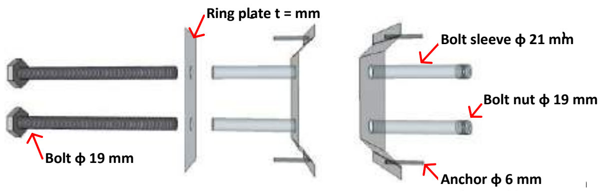
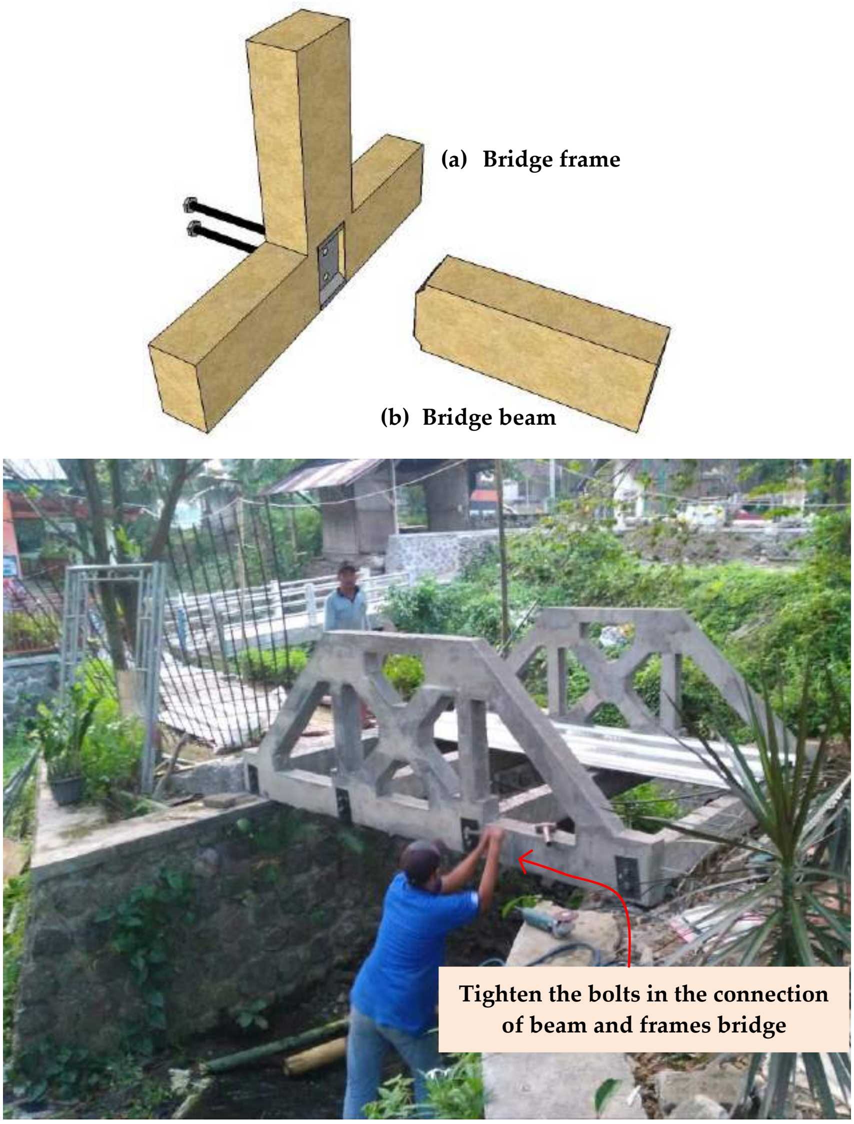


Figure 10. Details of ring plate and bolt sleeve



(a) Bridge frame

(b) Bridge beam

(c) Precast bridge frames

Figure 11. Models and applications of precast connections

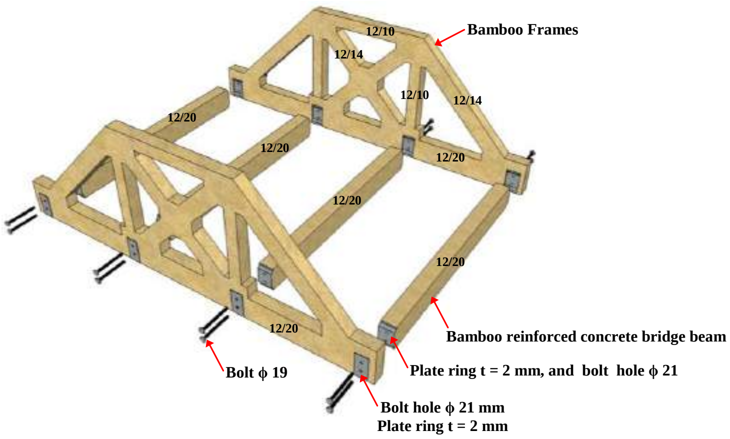


Figure 12. Model of the precast bridge from bamboo reinforced concrete

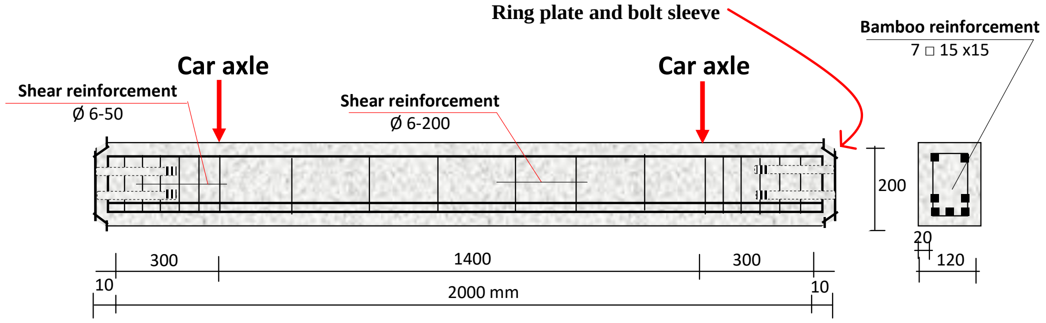


Figure 13. Details of Precast bridge beam reinforcement [12]

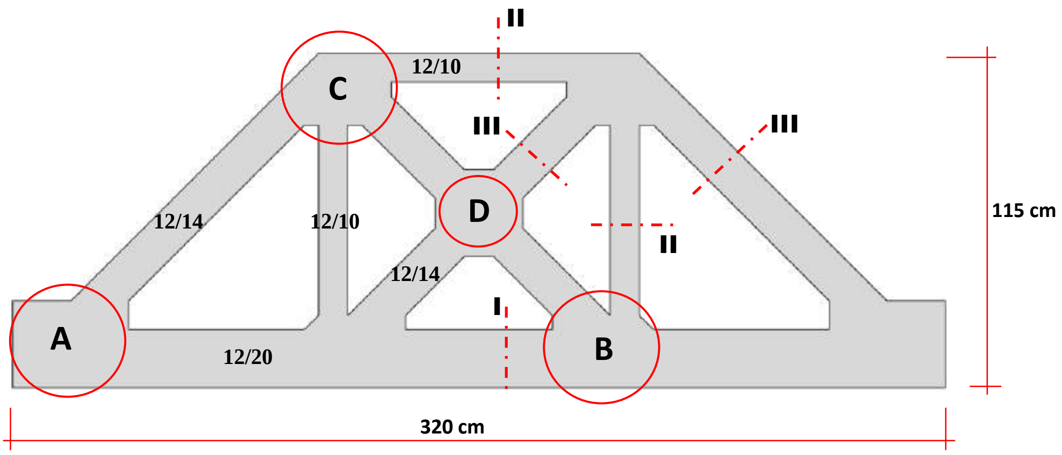
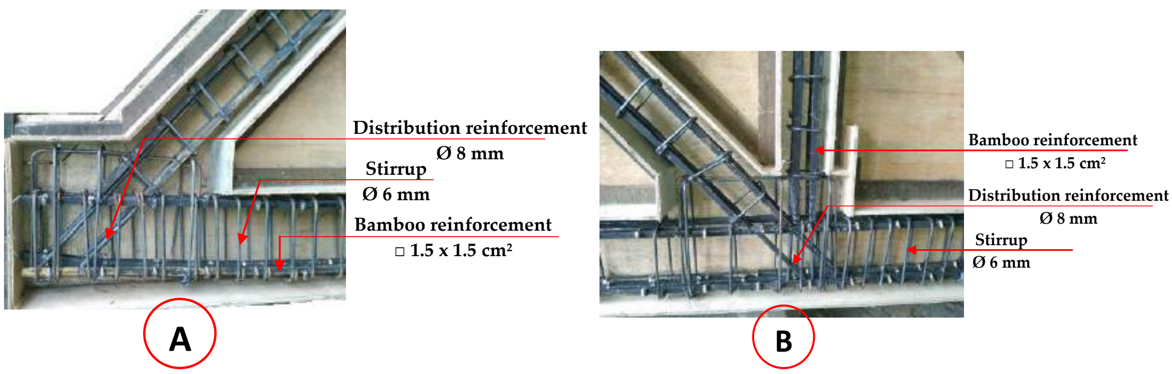


Figure 14. Details of precast bridge frame [23]



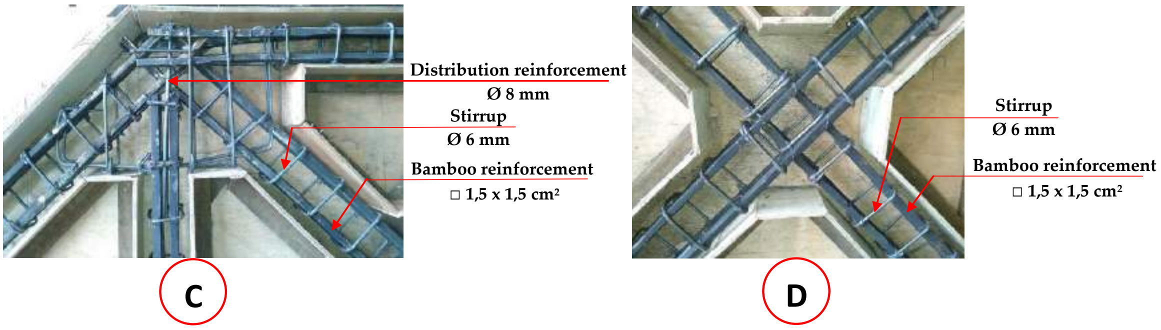
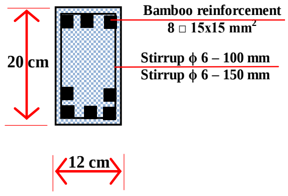
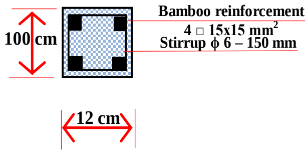
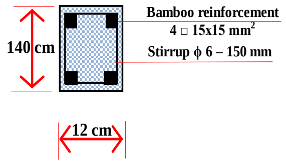


Figure 15. Details of knot reinforcement for bridge frames [23]

Table 4. Details of bridge frame reinforcement [23]

Model	**I (Shown in** Figure 14**)**	**II (Shown in** Figure 14**)**	**III (Shown in** Figure 14**)**
Rigid portal model or "frame model"			

Testing of precast bridges with bamboo reinforced concrete frames is carried out directly with a load of a minibus type vehicle. The load is given in stages and levels, starting from zero loads, Brio carload without passengers, Brio carload of full passenger, and AVANZA carload of the full passenger as shown in Figure 16. The stage of reading the response variable is carried out when the axle of the car is at coordinates 0 cm, 17.5 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 267.5 cm, and 300 cm from the support as shown in Figure 17. Tests are carried out on service limits or elastic conditions with displacement and deformation measuring parameters. To get the displacement that occurs in the beam and bridge frame, 4 LVDTs (Linear Variable Displacement Transducers) are installed with inductive transducers of type PR 9350 in the middle of the frame span and the middle span of the bridge beam. Meanwhile, to determine the deformation of the bridge, 6 pieces of LVDT were installed, 2 pieces of LVDT were installed in the middle of the side frame span, and 4 LVDTs were installed on the side of the four ends of the beam. The performance test settings for precast bridges of bamboo reinforced concrete frames are described in Figure 18.

The weight of the Brio car and the Avanza car is calculated based on the empty weight and the total passenger weight according to the capacity of the number of passengers. The calculation of passenger weight is based on the average weight of Indonesians, namely 65 kg. The calculation of the total weight of a minibus and its specifications are shown in Table 5.

Table 5. Specifications and weight of minibus car

Type of car	**Length**	**Height**	**Width**	**Wheelbase**	**Empty weight or one driver**	**Passenger capacity**	**Weight with full passenger**
	mm	**mm**	**mm**	**mm**	**kg**	**person**	**kg**
Brio	3800	1485	1680	2655	930 - 965	5	1280
Avanza	4190	1695	1660	2655	1045 - 1095	7	1550

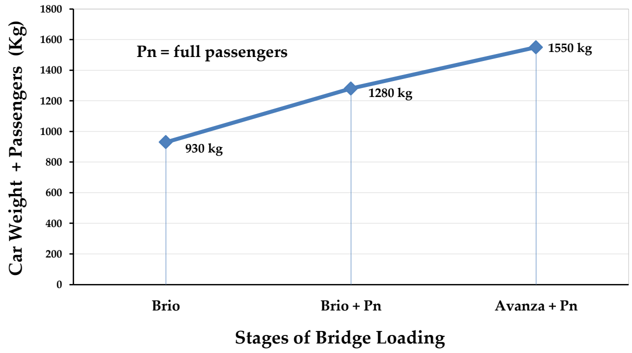
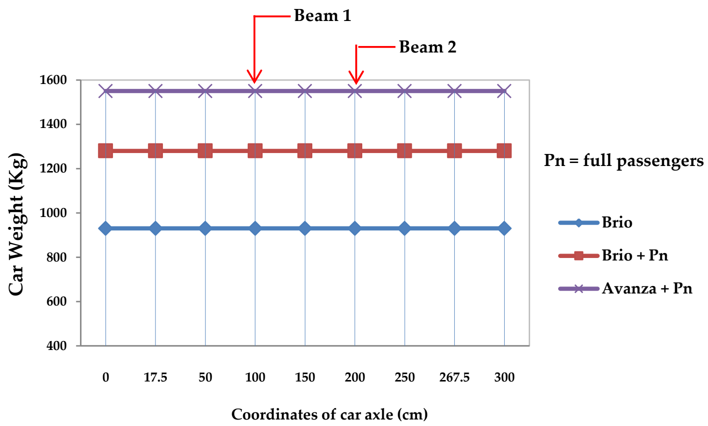


Figure 16. Loading stage of precast bridges of bamboo reinforced concrete frame



The Reading Plan of Displacement

Figure 17. The coordinates of the reading points of displacement and deformation

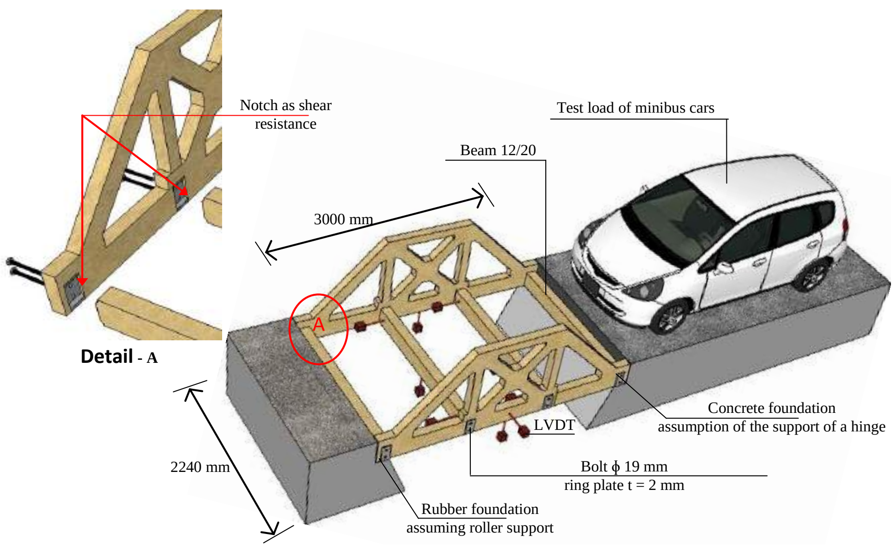


Figure 18. Arrangement of testing for bamboo reinforced concrete frame precast bridges

The planned life of the bridge is 10 years. The determination of the age of the bridge in this study is based on opinions and research on the resistance of bamboo as concrete reinforcement that has been carried out by several researchers including Hidalgo (1992) in Sattar (1995) [43], Ghavami (2005) [1], Rong BS (2007) [40], Lima Jr et al. (2008) [29]. After the design life of the bridge is reached, a gradual visual observation of the deflections and cracks will be carried out. Observations will be carried out every year with the main objective of observing the durability of bamboo as the concrete reinforcement of the bridge elements. Measured parameters during the observation period are deflection and cracks that may occur due to the decreased durability of bamboo reinforcement.

Hidalgo (1992) in Sattar (1995) [43] reports that a house in Colombia whose ceiling and walls are made of bamboo plastered with cement mortar can last for more than ninety years. Ghavami (2005) [1] mentions that after testing, bamboo reinforced concrete beams are left in the open air at the PUC Rio Brasil university campus, bamboo reinforcements from treated beams show that the bond with the concrete is still in satisfactory condition after 15 years. B.S. Rong (2007) [40], in his opening speech at the First International Conference On Modern Bamboo Structure (ICBS-2007) in Changsha, China, states that the bamboo reinforcement that is used as a substitute for steel reinforcement in precast floor plate elements for a five-story office building still functions well after more than fifty years of use, so bamboo reinforcement can be used as a substitute for steel reinforcement with the level of durability is good. Lima Jr et al. (2008) [29] experimented on the Dendrocalamus giganteus bamboo species showing that bamboo with 60 cycles of wetting and drying in a calcium hydroxide solution and tap water did not decrease its tensile strength and Young Modulus. This is an important factor in the material for use as concrete reinforcement.

2.3. The numerical method used

To determine the capacity and behavior of reinforced concrete structural elements can be done with a numerical approach. Theoretical analysis is carried out as control over the results of research in the laboratory so that the actual structural behavior differences can be seen with the theoretical analysis. The numerical method used is the finite element method (FEM). Numerical verification in this study was carried out to control the suitability of the deflection value of the experiment results with the deflection contours of the FEM analysis result. The program developed in the FEM analysis is written with the Fortran PowerStation 4.0 program. The theoretical analysis to calculate the load causing the initial crack using the elastic theory with the transformation section. The formula for the transformation of the cross-sectional bamboo reinforced concrete is shown in Equations (1) and Equations (2). For linear analysis, the material data entered are the Poisson's ratio (υ) and the modulus of elasticity (E). The constitutive relationship analysis of the problem-solving method uses the stress-field theory. Triangular elements are used to model the plane stress element with a two-way primary displacement at each nodal point so that the element has six degrees of freedom as shown in Figure 19. The stress-strain relationship for the field stress problem has the form of an equation such as Equation (3).

$$n = \frac{E_{Bamboo}}{E_{concrete}} \tag{1}$$

$$E_{Comp} = \frac{A_{Bamboo} x E_{Bamboo} + A_{Concrete} x E_{Concrete}}{A_{Comp}} \tag{2}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{4}$$

where E is the modulus of elasticity and ν is the Poisson's ratio. And the principal stresses in two dimensions are calculated by Equation (4). The Fortran PowerStation 4.0 programming language for triangle elements is shown at the following link: https://bit.ly/3l1oU0d.

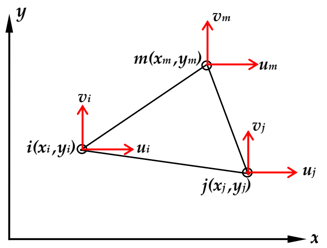


Figure 19. The degrees of freedom of triangular element

3. Results

Specifications for precast bridges of the bamboo reinforced concrete frame are shown in Table 6. The precast bridges were tested with a minibus car of the full passenger. The test is carried out after several stages of work are done, including making river stone foundations, making support plates, setting the frame on two supports, installing bridge beams and joints, casting bridge plates, completing or finishing the bridge. Recording of test results response starts when the front axle of the minibus car is right on the hinge support and ends until the rear axle of the minibus car is right on the support of the roller. The test result data is shown in Table 7.

The security measure during the test is to place the support poles and scaffolding under the bridge. The support poles and scaffolding under the bridge also function as a place and safety for the LVDT tool. Besides, the bridge is planned using the "Service Load Planning" method with the assumption that the structure has linear elastic behavior and the load test is carried out with elastic loads or under the initial crack load of the most critical bridge components. Observation of deflection and deformation that occurs is deflection and elastic deformation. The critical load (Pcr) or initial crack load is 2.1 tons and the maximum test load for minibusses is 1.55 tons.

Figures 20-25 show the beam displacement and the bridge frame with the minibus Brio car, Brio with full passengers, and AVANZA with full passengers. The maximum displacement with the load of the Brio car occurs when the position of the front axle is at coordinates 150 cm and the rear axle is at a distance of 85 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.14 mm for beam displacement. While the maximum displacement with a full passenger Brio car occurs when the position of the front axle is at coordinates 200 cm and the rear axle is at a distance of 35 cm from the pedestal, with a displacement of 0.2 mm for the frame and 0.17 mm for beam displacement. For maximum displacement with a full passenger AVANZA car load occurs when the front axle position is outside the bridge coordinates, which is 115 cm from the roller support, and the rear axle is at 150 cm coordinates, with a displacement of 0.25 mm for the frame and 0.21 mm for displacement beam.

Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum allowable displacement limit of the bridge is Δ_{max} = L/800 or equal to 3.75 mm. Thus, the maximum displacement that occurs in the element of the bamboo reinforced concrete frame bridge meets the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25].

Table 6. Geometry and specifications of precast bridges bamboo reinforced concrete frame

Bridge span	:	3 meters
Foundation	:	River stone
Bridge support	:	Concrete slab = assumption of hinge support; Concrete slabs and rubber pads = assumption of the roller support
Beam	:	- Dimensions of the bridge beam 12 x 20 cm^2, tensile reinforcement (ρ) = 4.688% and compressive reinforcement (ρ') = 1.875% - Hose-clamp d = ¾ ″attached to the end of the bamboo reinforcement instead of hooks. - Adhesive layers of bamboo reinforcement using Sikadur®-752 and sand

Connection type	:	Precast system connection, using bolts and sleeves of 19 mm diameter
Frame model	:	Rigid portal model or "frame model"
Bridge slab	:	- 10 cm thick slab + spandex t = 0.3 mm. - Slab reinforcement using bamboo 1.5 x 1.5 cm2 with a distance of 10 cm
Displacement and deformation of permit	:	Based on AASHTO [38] and RSNI T-12-2004 standards [25], the maximum displacement of permit is Δ_{max} = L/800 = 3.75 mm

Table 7. Data on the test results of the precast bridge of bamboo reinforced concrete frames

Bridge load	Displacement and deformation						
	Frame 1		Frame 2		Beam 1		Beam 2
	Displacement[1] (mm)	Deformation[2] (mm)	Displacement[1] (mm)	Deformation[2] (mm)	Displacement[1] (mm)	Deformation[2] (mm)	Displacement[1] (mm)
Brio 930 kg	0.2	0.03	0.04	0.04	0.06	0.01	0.14
Brio+Pn 1280 kg	0.2	0.01	0.04	0.05	0.08	0.06	0.17
Avanza+Pn 1550 kg	0.25	0.01	0.04	0.13	0.14	0.2	0.21

[1] Displacement is the deflection of the direction of gravity on the beam or frame elements due to the distribution of vehicle loads within the elastic limit. [2] Deformation is a change in shape or a change in the angle of the cross-section of the beam or frame due to the distribution of vehicle loads within the elastic limit measured in the direction of horizontal of the cross-section

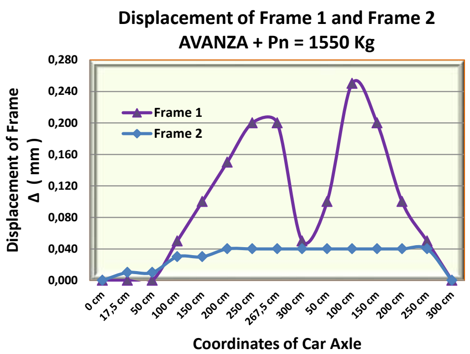


Figure 20. Displacement of the frame with loads of AVANZA car of full passengers

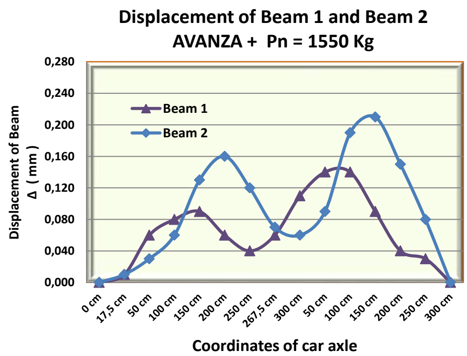


Figure 21. Displacement of the beam with loads of AVANZA car of full passengers

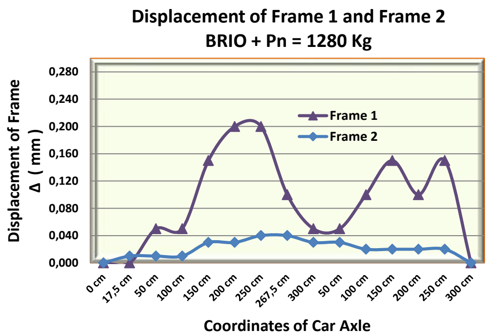


Figure 22. Displacement of the frame with loads of BRIO car of full passengers

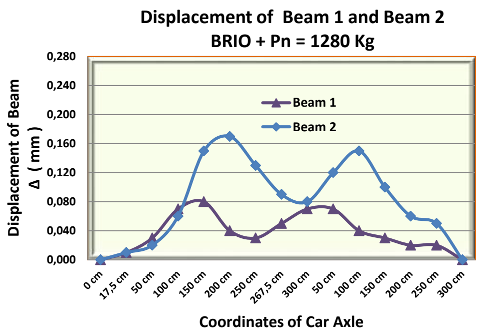


Figure 23. Displacement of the beam with loads of BRIO car of full passengers

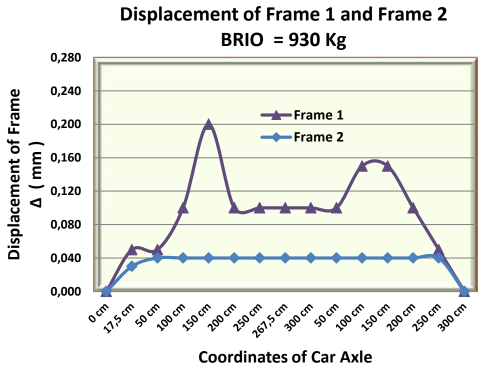


Figure 24. Displacement of the frame with loads of BRIO car of no passengers

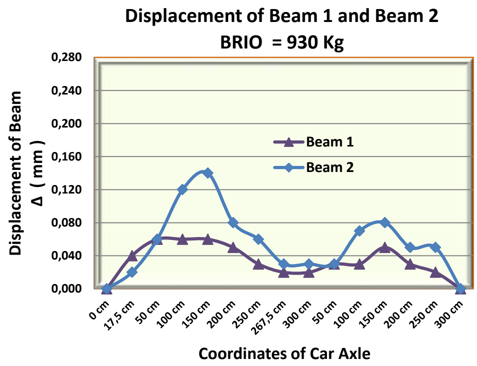


Figure 25. Displacement of the beam with loads of BRIO car of no passengers

Figure 26 shows the deformation of the bridge beam of bamboo reinforced concrete with a load of Brio minibusses car, Brio car with full passengers, and AVANZA car with full passengers. From Figure 26 and Table 7, it shows that the maximum deformation occurs in the beam with the load of the AVANZA car with a full passenger, which is when the position of the front axle is outside the coordinates of the bridge which is 65 cm from the roller support, and the rear axle is at coordinates 100 cm, with deformation a beam of 0.20 mm.

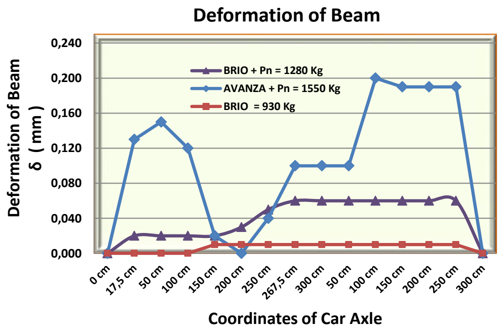


Figure 26. Deformation of the beam of the precast bridge of bamboo reinforced concrete

Figures 27-29 show that the deformation of the bridge frame with the load of the Brio minibus, Brio car with full passengers, and AVANZA car with full passengers. Maximum deformation with the brio car load occurs when the position of the front axle is outside the coordinates of the bridge, which is 85 cm from the roller support, and the rear axle is at coordinates 150 cm, with frame deformation of 0.04 mm.

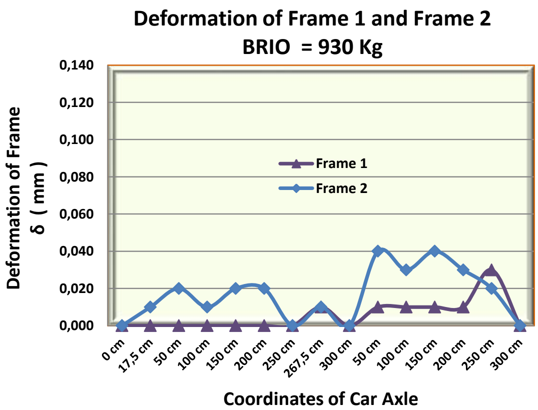


Figure 27. Deformation of the frame with loads of BRIO car of no passengers

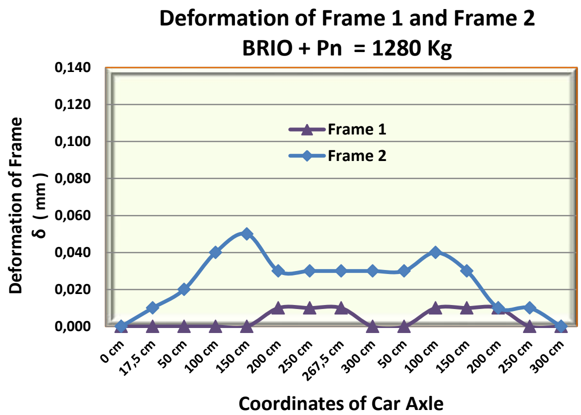


Figure 28. Deformation of the frame with loads of BRIO car of full passengers

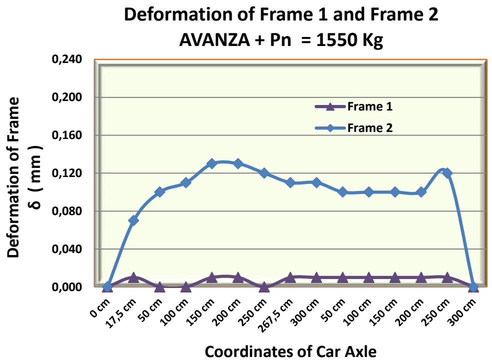


Figure 29. Deformation of the frame with loads of AVANZA car of full passengers

While the maximum frame deformation with the load of the brio car with full passengers occurs when the position of the front axle is at coordinates 150 cm and the rear axle is at a distance of 85 cm from the hinge support, with deformation of 0.05 mm. For the maximum deformation of the frame with the load of the AVANZA car with full passengers occurs when the position of the front axle is at the coordinates of the bridge is 150 cm, and the rear axle is at a distance of 115 cm from the hinge support with deformation of 0.13 mm.

4. Discussion

Deformation usually occurs due to shrinkage of concrete, deformation of precast connections, foundation settlement, or due to static load or dynamic loads on the bridge. In this study, deformation or elastic deformation is a change in shape or change in the angle of the cross-section of the beam or frame due to the distribution of vehicle loads within the elastic limit measured in the horizontal direction of the cross-section. Measurements were made by installing LVDT (*Linear Variable Displacement Transducers*) with inductive transducers of type PR 9350 on the horizontal side of the frame and bridge beams as shown in Figure 30.

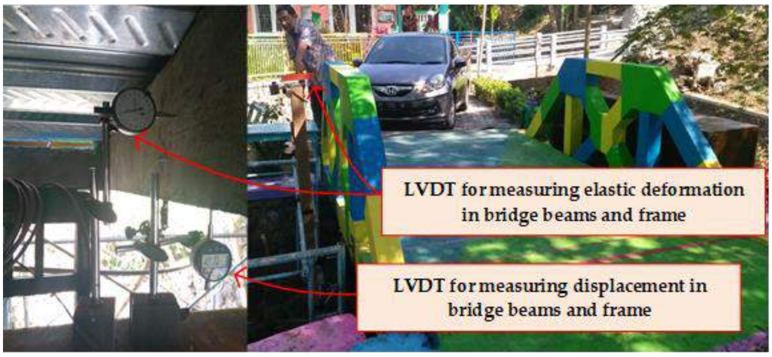


Figure 30. The measuring elastic displacement and deformation

The accuracy of deformation measurement is very much determined by the calibration of the equipment, the accuracy of the load point of the observation, the conditions of the test site such as near roads, and human error. Figure 26 shows that the minimum beam deformation occurs when the car axle is right on the neutral line of the beam, this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity loads right on the neutral line can reduce deformation and increase the deflection of the bridge beams. Figure 26 and Figure 21 at 200 cm coordinates show that when the beam deformation is minimum, the beam displacement is maximum. As shown in Figure 17, Beam 1 is at coordinates 100 cm and Beam 2 is at coordinates 200 cm. The deformation of the beam increases in line with the track of the car axle, that is, the deformation continues to increase, respectively, of the front car axle and rear car axle. However, the accuracy of deformation measurements needs attention to many determinants of accuracy.

Figure 27 and Figure 28 shows that minimum frame deformation or deformation = 0 occurs when the car axle is directly above the pedestal or approaching the pedestal. Meanwhile, the maximum frame deformation occurs when the car axle is in the middle of the bridge span, which is at coordinates 150 cm. There is a difference in the deformation of the bridge beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is the middle of the bridge span or at 150 cm coordinates. It must be remembered that careful preparation at the time of testing or measurement must be considered so that the data obtained is truly accurate, as shown in Figure 27 the coordinates of 250 cm occur inconsistent deformation data even though the car axle is close to the support.

Table 7 shows that the maximum deformation of the bridge frame is 0.13 mm and the maximum displacement of the bridge beam is 0.20 mm. According to the AASHTO [38] and RSNI T-12-2004 standards [25], the allowable limit for the maximum displacement is Δ_{max} = L/800 = 3.75 mm and the maximum deformation of the bridge is δ_{max} = L/800 = 3.75 mm. Thus, the maximum deformation and displacement that occurs in the precast bridge elements of the bamboo reinforced concrete frame meet the requirements based on AASHTO [38] and RSNI T-12-2004 standards [25]. However, the relationship of load vs. displacement of beam and frame results from field experiments need to be validated or controlled with the relationship of load vs. displacement of laboratory experimental results and simulation results of numerical methods. The simulation in this study used the finite element method (FEM).

The simulation of the bridge frame test using the finite element method (FEM) was carried out using the Fortran PowerStation 4.0 program and surfer 9.8 software [26] based on laboratory test results. Simulations were carried out as control and validation of experimental data. The bridge frame test simulation is carried out at the first crack load stage, which is 87 kN based on the frame loading capacity of only 100 kN. The discretization of the Bamboo Reinforced Concrete Bridge Frame for the finite element method (FEM) is shown in Figure 31. The Y-direction and X-direction displacement are shown in Figure 32 and Figure 33. The loading stages and Y-direction displacement of the finite element method simulation results are combined with the load vs. displacement laboratory test results [23] and field test results as shown in Figure 34. Figure 33 shows displacement in the x-direction, green color shows minimum displacement, orange, and blue color shows the maximum positive and negative displacement. FEM analysis modeling on the bamboo reinforced concrete frames can be seen in item 2.3 the numerical method used.

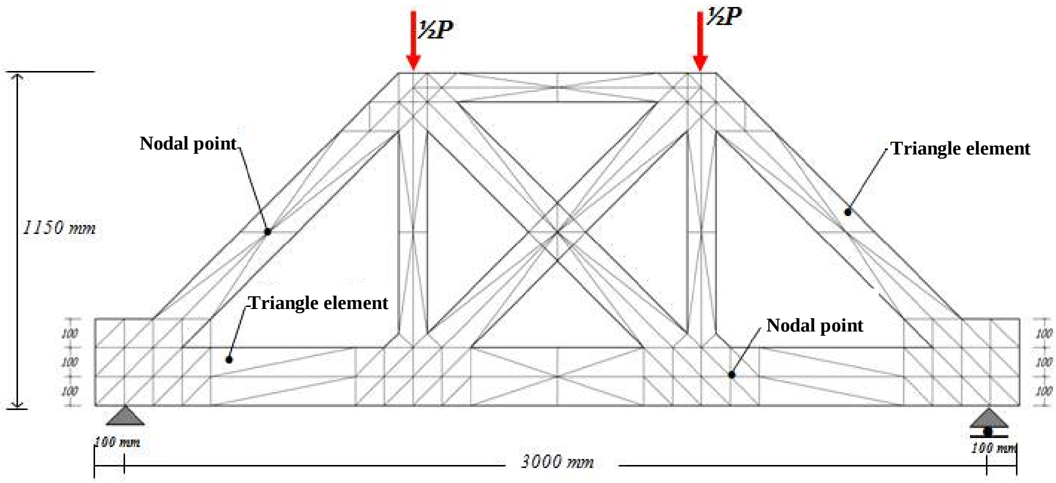


Figure 31. Discretization of Bamboo Reinforced Concrete Bridge Frames

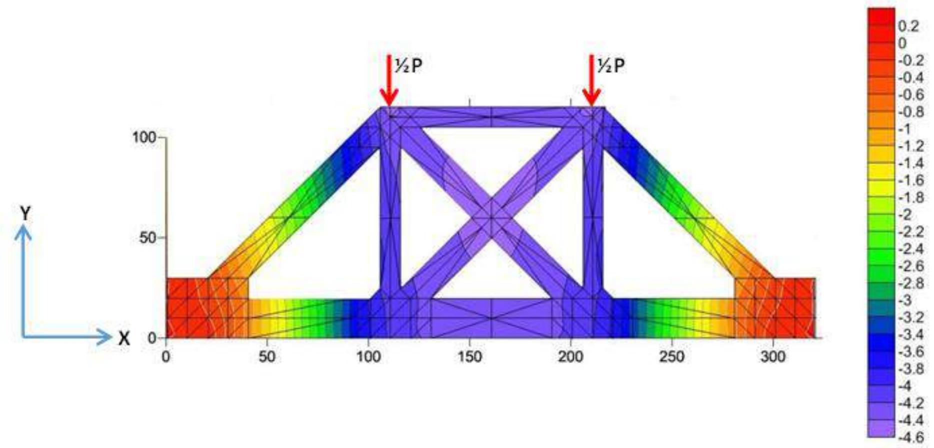


Figure 32. The displacement of Y-direction of the bridge frame

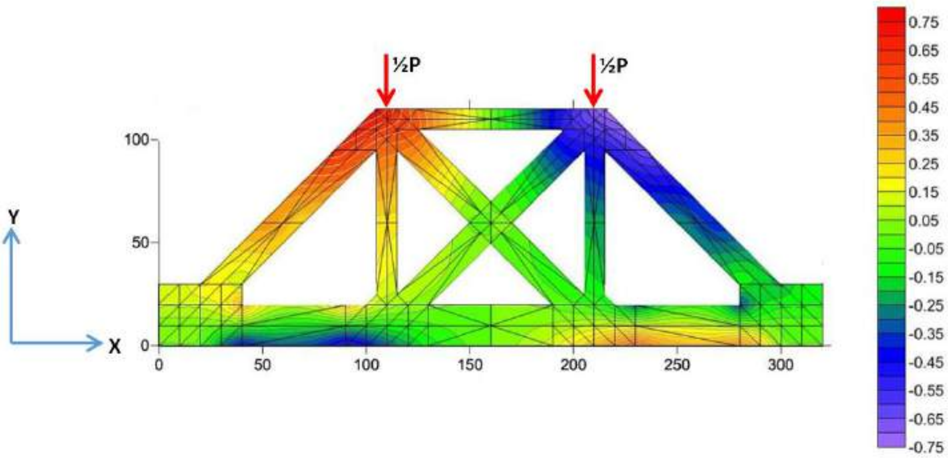


Figure 33. The displacement of X-direction of the bridge frame

Bridge integrity is the ability of a bridge structure or bridge components to withstand the designed load, preventing structural collapse due to cracks or fractures, deformation, and structural fatigue. Structural integrity is a concept used for the design plan and designing service load. Stiffness is the main parameter of the resistance of a bridge structure to get good bridge integrity [7]. The stiffness of the elements of the bridge structure needs to be controlled to prevent sudden collapse due to cracking and excessive deformation. Stiffness control of beams and bridge frames is analyzed through a combination of load vs. displacement from the simulation results of the finite element method (FEM), the results of laboratory experiments [12,23], and the results of field experiments as shown in Figure 34. Control is carried out at the maximum load point of the bamboo reinforced concrete precast frame bridge test in the field, which is 15.5 kN as shown in Figure 35 and Figure 36. Documentation of the direct test of bamboo reinforced concrete precast bridges can be seen at the following link: https://bit.ly/3gzaW30.

Calculation of aerodynamic effects due to wind loads and dynamic analysis on precast concrete bamboo bridges were not carried out. Based on the Earthquake Resistance Standard for Bridges, SNI SNI-07-SE-2015 [39] dynamic analysis needs to be carried out for bridge types with complex behavior, one of which is the main span exceeding 200 meters. In this study, the bridge width is 2.24 meters and the bridge span is 3.20 meters, and the ratio of the bridge width to the bridge span of 0.7 is still stable against aerodynamic effects due to wind loads according to Leondhart's requirements ($B \geq L/25$) and still meets the maximum deflection requirements. AASHTO [38] and RSNI T-12-2004 [25] that is Δ_{max} = L/800 = 3.75 mm.

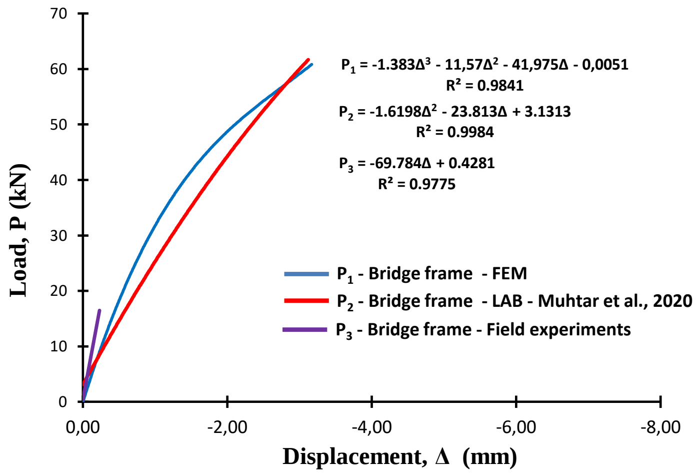


Figure 34. The relationship of load vs. displacement of the bridge frame

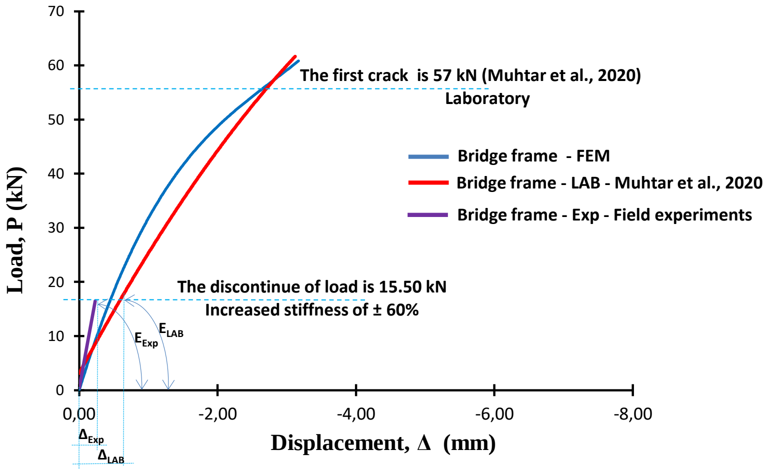


Figure 35. The relationship of load vs. displacement of bridge frame from laboratory test results, FEM results, and field experiment results

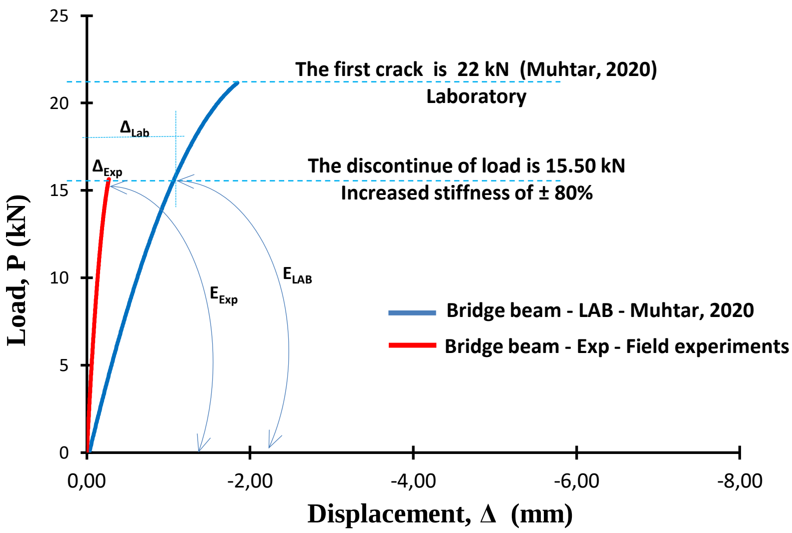


Figure 36. The relationship of load vs. displacement of bridge beam from laboratory test results and field experiment results

The next step is validating the stiffness of the beam and bridge trusses. The main principle is that the bridge must be in a service condition with a Serviceability Limit State (SLS) load. The elements of the bridge structure should not be subjected to cracks, deflection, or vibrations causing user discomfort. The allowable deflections are those that are elastic deflection and do not cause the crack. Stiffness is the main parameter of structural resistance. Therefore, the stiffness of the field test results needs to be validated by the stiffness of the laboratory test results. Load-displacement relationship diagrams of experimental results, laboratory results, and FEM analysis results are combined into one graph. The maximum test load of the bridge becomes the stiffness control limit, which is 15.50 kN. Based on the displacement of the laboratory test results and the displacement of the field experiments results of the bamboo reinforced concrete frame precast bridge at a stop load of 15.50 kN, obtained the displacement ratio of the laboratory test results to the displacement of the field experiment results ($\Delta_{Exp}/\Delta_{LAB}$) = 2.6 for the bridge frame, and 4.07 for the bridge beam. Figure 35 and Figure 36 shows that the stiffness of the precast bridge beam and precast bridge frame increases ± 80% for the beam stiffness and increases ± 60% for the frame stiffness if it is used as an integral part of other bridge elements.

5. Conclusions

Based on the results of laboratory tests and field experiments, it appears that the bridge displacement is quite small and comfortable for the user. The maximum beam displacement occurs when the rear wheel is at the center of the span of 150 cm coordinates and the front wheel is at 415.5 cm coordinates (the front wheel is outside the bridge). While the maximum displacement of the frame occurs when the rear wheel is at coordinates 100 cm and the front wheel is at coordinates 365.5 cm (the front wheel is outside the bridge).

The minimum beam deformation occurs when the car axle is right on the neutral line of the beam, this shows that the coupling moment or torque due to the load is a factor that greatly affects the size of the beam deformation. Gravity load right on the neutral line can reduce deformation and increase the deflection of the beam and bridge frame, and the size of the torque moment can affect the size of the deformation.

There is a difference in the maximum deformation occurrence between the beam and the bridge frame, namely the maximum beam deformation occurs when the load is outside the beam coordinates, while the maximum frame deformation occurs when the load is in the middle of the bridge span and outside the frame coordinates.

Precast bamboo reinforced concrete frame bridges have sufficiently good integrity, that is, they can distribute loads with deflection and deformation that do not exceed their permits. The maximum displacement of 0.25 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than Δ_{max} = L/800 = 3.75 mm. The maximum deformation occurs in the bridge beam of 0.20 mm, and the bridge frame of 0.13 mm meets the requirements based on the AASTHO and RSNI T-12-2004 standards, which is not more than δ_{max} = L/800 = 3.75 mm.

At the stop load P = 15.5 kN, the stiffness of the bridge beam increased ± 80% during the bridge test, when compared with the beam stiffness of the laboratory results. Likewise, the stiffness of the bridge frame increased ± 60% during the bridge test, when compared to the frame stiffness of the Laboratory results.

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Conflicts of Interest: The authors declare no conflict of interest.

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