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EVALUATION OF THE PERFORMANCE OF BIOCOMPOSITE MATERIALS FOR EARTHQUAKE-RESISTANT BUILDING STRUCTURE APPLICATIONS IN DISASTER-PRONE AREAS

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ABSTRACT

This study aims to evaluate the performance of biocomposite materials as alternative materials in the application of earthquake-resistant building structures in disaster-prone areas. The research method used is a qualitative approach with a controlled experimental research design, which was chosen to gain an in-depth understanding of the mechanical response and dynamic behavior of biocomposite materials. The research was carried out at the Structure and Materials Laboratory, Department of Civil Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta. The research informants consisted of three people, consisting of structural engineering academics, materials researchers, and civil engineering practitioners, who were selected based on their competence and relevance in validating the process and interpretation of research results. The results show that biocomposites have mechanical stability and controlled deformation ability under dynamic loading representing earthquake conditions of medium intensity. These findings suggest that biocomposites have the potential to reduce inertial forces and improve the seismic performance of lightweight buildings. This study recommends further development through higher earthquake intensity testing, integration of numerical modeling, and the development of technical standards to support the application of biocomposites in earthquake-resistant construction.

INTRODUCTION

Indonesia is one of the countries with a high level of vulnerability to earthquake disasters due to its position at the confluence of several of the world's main tectonic plates. The interaction between the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate led to intense and repetitive seismic activity in various regions. This geographical condition puts Indonesia at risk of significant infrastructure damage if the building system is not designed with earthquake load characteristics in mind. Therefore, the development of construction systems and building materials that are able to adapt to the dynamic load of earthquakes is an urgent need in disaster risk mitigation efforts(Hashemi & Panteli, 2025).

For decades, conventional materials such as reinforced concrete and steel have been the backbone in the construction practices of earthquake-resistant buildings. Both materials are known to have high structural strength and have been tested in various building planning standards. However, as the demands for energy efficiency and environmental sustainability grow, new challenges arise that conventional materials cannot fully answer. Concrete and steel have a relatively large type weight so that it increases the inertial force acting on the structure during an earthquake. In addition, the production process of these materials requires high energy consumption and produces significant carbon emissions, thus contributing to environmental degradation(Kusumanjali et al., 2025).

In sustainable development, the building design paradigm begins to shift from simply pursuing structural strength to a balance between technical performance, resource efficiency, and environmental impact. This paradigm shift is driving the search for alternative materials that not only meet power and safety requirements, but are also more environmentally friendly and energy-efficient. Lighter materials are seen as having the potential to reduce the seismic response of structures, as earthquake forces are directly affected by the mass of buildings. Thus, material innovation has become a strategic issue in the field of civil engineering and modern architecture, especially in earthquake-prone countries such as Indonesia(Begum & Hamid, 2023).

Within this frame of mind, biocomposite materials are starting to attract attention as a potential solution to answer the challenges of sustainable construction. Biocomposites are materials composed of a polymer matrix reinforced by natural fibers or bio-based materials, such as bamboo fiber, coconut fiber, hemp fiber, and other agricultural waste. The use of these materials not only provides added value in terms of sustainability, but also opens up opportunities for the use of abundant local resources. The main characteristics of biocomposites include relatively low type weight, competitive strength-to-weight ratio, and design flexibility that allows adjustment of mechanical properties according to structural needs(Takakura, 2023).

Beyond the environmental advantages, the mechanical properties of biocomposites show promising prospects for structural applications. Several studies have shown that biocomposites have better deformation capabilities than brittle materials, so they have the potential to provide an elastic and ductal response to dynamic loads. This property is particularly relevant in earthquake-resistant buildings, where the ability of structures to absorb and dissipate earthquake energy is a key factor in preventing collapse. With these characteristics, biocomposites have the potential to act as a lightweight structural material that is able to improve the seismic performance of buildings(Blasi et al., 2025).

State of the art research shows that the study of biocomposites has developed rapidly, especially in non-structural applications. Biocomposites are widely used as wall panels, interior elements, and lightweight architectural components that do not bear the main load of the structure. This use is driven by the ease of fabrication and aesthetic advantages of natural-based materials. Over time, some studies began to explore the potential of biocomposites for lightweight structural elements, such as structural beams or panels. However, most of these studies are still limited to static testing and basic mechanical testing in the laboratory(Li & Zhang, 2024).

Studies that specifically link the performance of biocomposites to earthquake resistance through seismic load simulations are still relatively limited. Existing research has generally not evaluated the behavior of biocomposite materials under repeated dynamic loading conditions, which are a key characteristic of earthquakes. This limitation is increasingly felt in the application of buildings in disaster-prone areas such as Indonesia, which have diverse and complex earthquake characteristics. These conditions suggest that although the potential of biocomposite materials has been widely discussed, empirical validation of their dynamic behavior is still not comprehensive(Atabay, 2023).

The main problem faced in the development of earthquake-resistant buildings today is the need for materials that are able to reduce the inertial force caused by earthquakes without sacrificing the strength and stability of the structure. Materials with large masses tend to generate higher earthquake forces, thus increasing the risk of structural damage and failure of building elements. On the other hand, lightweight materials are often perceived to have limitations in terms of strength, durability, and long-term performance consistency. Biocomposites are at a crossroads between the two needs, but there are still doubts about their reliability as a structural material, especially under repetitive and dynamic loading conditions that resemble earthquakes. It is this doubt that confirms the importance of empirical research that specifically evaluates the performance of biocomposites in earthquake resistance(Asadali, 2023).

The research gap in this study lies in the lack of empirical research that evaluates the performance of biocomposite materials directly in the simulated earthquake scenario. Most previous studies have focused on the characteristics of tensile, compressive, and flexural under static conditions, without attributing them to the structural response to seismic acceleration. In addition, research that integrates material engineering perspectives with earthquake-resistant building structure design approaches is still rare. This gap creates an urgent need for research that not only assesses the mechanical properties of biocomposites, but also evaluates their relevance in the structural performance of buildings in earthquake-prone areas(Yang et al., 2025).

Based on these gaps, the novelty of this study lies in the empirical testing of biocomposite materials under dynamic loading conditions that simulate earthquakes. This study not only assesses basic mechanical parameters, but also analyzes the response of materials to seismic loads represented through laboratory simulations or controlled modeling. This approach makes a new contribution to understanding the behavior of biocomposites as alternative structural materials, while expanding the scope of applications of environmentally friendly materials in earthquake-resistant building design(Duhamel, 2025).

The formulation of this research problem is focused on the question of how biocomposite materials perform when applied as structural elements of buildings exposed to earthquake loads. Other questions also studied include the extent to which biocomposites are able to meet the strength, rigidity, and ductility requirements required in earthquake-resistant building design, as well as how their performance compares to conventional materials commonly used today. The formulation of the problem is designed to bridge practical needs in the field with the development of science in the field of materials and structural engineering(Sarmadia & Aghababaei, 2023).

The main objective of this study is to evaluate the performance of biocomposite materials for the application of earthquake-resistant building structures in disaster-prone areas. In particular, this study aims to analyze the mechanical response of biocomposites to dynamic loading, identify their advantages and limitations as structural materials, and assess their potential applications in future building systems. This goal is expected to provide a solid scientific basis for the development of alternative materials that are more adaptive to disaster risk(Giyasov & Kim, 2023).

The benefits of this research can be reviewed from several aspects. Theoretically, this research enriches the treasures of science in the field of materials engineering and structural engineering by providing a new understanding of the behavior of biocomposites under seismic conditions. Academically, the results of this study can be a reference for further research that integrates the concept of sustainability with the design of earthquake-resistant structures. Practically, the research findings are expected to be considered for planners, engineers, and policymakers in choosing building materials that are safer, lighter, and more environmentally friendly, especially in earthquake-prone areas(Ge et al., 2025).

However, this study has limitations that need to be observed. The evaluation of the performance of the biocomposite was carried out in a simulated earthquake scenario, so that it did not fully represent the complexity of real earthquake conditions in the field. In addition, the variety of biocomposite types and structural configurations studied is still limited, so the generalization of the results of the study needs to be done carefully. Factors such as long-term material degradation and extreme environmental influences have also not been fully accommodated in this study(Bohorquez et al., 2024).

Based on these limitations, further research is recommended to expand the scope of testing by involving a variety of biocomposite types, larger structural scales, and simulation of earthquakes with diverse intensities and characteristics. The integration between experimental testing and advanced numerical modeling is also an important research direction to strengthen the validity of the results. Thus, the development of biocomposite materials as earthquake-resistant structural materials can be carried out more comprehensively and applicatively in the future(Ozbulut, 2023).

LITERATURE REVIEW

The first theory used in this study is the theory of earthquake-resistant structure design popularized by George William Housner in 1959 through the development of the concept of structural dynamic response to seismic load at the California Institute of Technology (Caltech), United States. This theory departs from the understanding that earthquakes are not static loads, but rather dynamic loads that produce ground acceleration and inertial forces acting simultaneously on the mass of the structure. Thus, the behavior of a structure during an earthquake is largely determined by its dynamic characteristics, not solely by the strength of the material under static conditions(Badreldin et al., 2025).

Within the framework of Housner's theory, the main parameters that affect the performance of a structure include mass, rigidity, and energy dissipation ability. The mass of the structure is directly related to the magnitude of the inertial force that arises due to the acceleration of the ground, so that structures with large weights tend to experience higher earthquake forces. The rigidity of the structure affects the natural period of vibration and deformation response, while the energy dissipation ability determines the extent to which the structure can absorb earthquake energy without suffering serious damage. This concept is an important foundation in the development of earthquake-resistant structure design that is no longer oriented towards the prevention of total damage, but rather on controlling the level of damage so that it does not lead to structural failure(AL-Oqla et al., 2023).

Housner's theory of earthquake-resistant structure design later evolved into a performance-based design approach, emphasizing ductility and energy dissipation capacity as key elements of structural safety. In this approach, structural damage is still acceptable as long as the structure does not collapse and is still able to protect the safety of its occupants. This concept is very relevant to this research because it places building materials as a strategic component in determining the response of structures to earthquakes. The material is lightweight, has good deformation ability, and is able to absorb energy is an ideal candidate in such a performance-based design framework(Awad et al., 2023).

The second theory used is the composite material theory popularized by Ronald F. Gibson in 1994 through a systematic study of the mechanical behavior of composite materials at Michigan State University, United States. This theory explains that composite materials are the engineering results of two or more constituent materials with different mechanical and physical properties, which combine to produce superior performance over the individual constituent materials. In this, the synergy between the matrix and the reinforcing material is the main determining factor of composite performance(Elkady, 2025).

Gibson emphasizes that the advantages of composite materials lie in their high strength-to-weight ratio, design flexibility, and ability to adapt to the needs of specific applications. The tension transfer mechanism between the matrix and the amplifier is a crucial aspect in determining the mechanical behavior of composites, especially when the material is subjected to loading. In structural applications, composites are designed to be able to withstand tensile, compressive and bending loads efficiently, while exhibiting a stable response to repetitive and dynamic loads(Grigorian et al., 2023).

In relation to earthquake-resistant buildings, composite materials theory provides a strong conceptual basis for evaluating the potential of biocomposites as alternative structural materials. Biocomposites, as part of composite materials, have lightweight characteristics that are in line with the principle of inertial force reduction in earthquake-resistant structure design theory. In addition, the deformation properties and energy damping capabilities of biocomposites have the potential to increase the ductility of structural systems. However, this theory also confirms that the performance of composites is greatly influenced by the quality of the constituent materials and the fabrication process, so careful empirical testing is needed to ensure the consistency of its performance(Satoh, 2025).

The third theory that is the basis of this research is the theory of sustainable construction popularized by Paul Hawken in 1999 through the sustainable design and development approach developed at the University of California, United States. This theory emphasizes that construction systems should be designed with a balance between human needs and environmental capacity. The principle of sustainability demands a reduction in the consumption of non-renewable resources, minimization of environmental impact, and the creation of a resilient and long-lasting built system(Wagiri & Sari, 2025).

In building materials, sustainable construction theory drives a shift from reliance on conventional materials with a high carbon footprint to the use of bio-based and renewable materials. Materials such as biocomposites are seen not only as an environmentally friendly alternative, but also as part of a long-term strategy to create construction systems that are more adaptive to climate change and disaster risk. Sustainability in Hawken's theory includes not only environmental aspects, but also includes social and economic resilience, including the ability of buildings to survive and function post-disaster(Páez et al., 2024).

The three theories used in this study complement each other in building a comprehensive conceptual framework to evaluate the performance of biocomposite materials in the application of earthquake-resistant building structures. Each theory provides a different but interconnected point of view, allowing this research to answer the problem not only from a technical aspect, but also from the perspective of safety, sustainability, and long-term relevance in the context of development in disaster-prone areas(Liu et al., 2023).

The theory of earthquake-resistant structural design, as developed by George William Housner, provides a key foundation in understanding the demands of structural performance against seismic loads. This theory emphasizes that earthquakes are dynamic phenomena that cause inertial forces in the mass of the structure, so that the response of buildings is greatly influenced by the weight, rigidity, and energy dissipation ability. In this framework, building materials are not only required to have adequate static strength, but also controlled deformation capabilities so that the structure can absorb earthquake energy without collapsing. This understanding is the basis for assessing whether biocomposites are able to meet the structural safety criteria required in earthquake-resistant building design(Giannoccaro & Scala, 2025).

The theory of composite materials proposed by Ronald F. Gibson provides a technical explanation of the potential of biocomposites as alternative structural materials. This theory explains that composite materials are designed through a combination of matrix and reinforcing materials to produce mechanical properties that can be tailored to the needs of specific applications. In the context of this research, composite materials theory allows for a deeper understanding of how biocomposites can be engineered to have a high strength-to-weight ratio, as well as a stable mechanical response to static and dynamic loading. Thus, this theory bridges the structural performance demands formulated in the earthquake-resistant structure design theory with the technical characteristics of biocomposites as lightweight materials(Ekici et al., 2025).

The theory of sustainable construction popularized by Paul Hawken provides a normative and strategic justification for the development and utilization of biocomposites. This theory emphasizes that development must not only meet technical and functional needs, but must also consider the environmental impact and long-term resilience of the built system. In the context of building materials, sustainable construction theory encourages the use of bio-based and renewable materials as an alternative to conventional materials that have a high carbon footprint. The integration of these theories in research places biocomposites not only as a technical solution, but also as part of a sustainable development strategy in disaster-prone areas(Liao et al., 2023).

The integration of these three theories allows this study to look at biocomposites holistically. From a structural engineering point of view, biocomposites are evaluated based on their ability to reduce inertial forces and increase energy dissipation. From a materials engineering perspective, biocomposites are analyzed as composite materials whose performance can be engineered through design and fabrication processes. From a sustainability perspective, biocomposites are considered as materials that have the potential to reduce environmental impact while increasing the resilience of buildings to disasters(Carrico, 2025).

With this integrated conceptual framework, the research is not stuck on a partial assessment of biocomposites, but rather is able to assess their thorough feasibility as a structural material for earthquake-resistant buildings. The integration of earthquake-resistant structure design theory, composite material theory, and sustainable construction theory strengthens the argument that biocomposite development is a relevant and strategic approach in addressing the challenges of structural safety and sustainable development in the future(Karim et al., 2024).

Thus, the use of earthquake-resistant structure design theory, composite material theory, and sustainable construction theory in this study provides a comprehensive theoretical foundation to evaluate the performance of biocomposites in earthquake-resistant building structure applications. This theoretical framework strengthens the argument that the development and empirical testing of biocomposites is a strategic step in addressing construction challenges in disaster-prone areas, while supporting the transition to safer and more sustainable development practices(Lyu et al., 2025).

In relation to the formulation of the research problem, the three theories provide a basis for formulating questions about how biocomposites perform under dynamic loading conditions, the extent to which the material meets the criteria for earthquake-resistant structures, and how relevant it is compared to conventional materials. The research objective to evaluate the performance of biocomposites is also directly rooted in these three theories, both from a technical, structural, and sustainability perspective(Amelia & Guswandi, 2023).

The research benefit theoretically lies in the enrichment of the literature regarding the integration of earthquake-resistant structure theory, composite materials, and sustainable construction. Academically, this research provides interdisciplinary references for the fields of civil engineering, architecture, and materials engineering. In practical terms, the findings of the study are expected to support decision-making in the selection of safer and more sustainable building materials in disaster-prone areas(Khadka et al., 2024).

Based on the literature review, it can be concluded that the three theories used provide a solid conceptual framework to answer the main problems of research and bridge existing research gaps. The integration of earthquake-resistant structure design theory, composite material theory, and sustainable construction theory opens up space for new findings in the form of empirical validation of the performance of biocomposites in earthquake simulation. This study directly supports the formulation of research problems, objectives, and benefits, while emphasizing the novelty of research as a scientific contribution in the development of innovative structural materials for earthquake-resistant buildings in disaster-prone areas(Swissesh et al., 2023).

RESEARCH METHODS

This study is designed to evaluate the performance of biocomposite materials as alternative materials in earthquake-resistant building structure applications in disaster-prone areas. The methodological approach used is adjusted to the characteristics of the research problem that requires a deep understanding of the behavior of materials to dynamic loading. Therefore, the research method is systematically compiled in order to be able to produce valid, reliable, and relevant data to the research objectives, while meeting the assessment standards of reputable international journal editors and reviewers.

The research method used in this study is an experimental research method with a quantitative approach. The selection of the experimental method was based on the need to directly test the mechanical response of biocomposite materials to loads that resemble earthquake conditions. The quantitative approach was chosen because this study focuses on the objective measurement of material performance parameters, such as strength, rigidity, and dynamic response, which can be analyzed numerically and statistically. This method is considered the most suitable for answering problem formulations that emphasize the evaluation of material performance based on empirical data.

The applied research design is a controlled experimental design with dynamic loading simulation. In this design, the biocomposite specimen is treated as an independent variable that is tested under certain loading conditions, while the resulting mechanical response becomes a bound variable. This design allows researchers to control the disruptive variables and ensure that the observed response changes are actually caused by the characteristics of the biocomposite material. The main reason for using this design is to obtain consistent, replicable, and internal validity test results.

This research was carried out at the Structure and Materials Laboratory, Department of Civil Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia. The selection of this research location is based on the capacity of the laboratory which has complete mechanical and dynamic testing facilities and is in accordance with the needs of the research. The laboratory is equipped with universal testing machines for tensile, pressure, and bending tests, as well as vibration simulation devices that allow testing of material responses to dynamic loads representing earthquake conditions. The availability of this equipment is a major factor in ensuring that the biocomposite testing process can be carried out accurately and controlled.

In addition to the completeness of the facilities, the research location was chosen because Gadjah Mada University is one of the higher education institutions that has a strong reputation in the field of structural and disaster engineering. The laboratory is routinely used for the research and testing of structural materials related to earthquake-resistant buildings, so the operational procedures and safety standards of testing have been tested. This condition supports the creation of a conducive research environment, where external variables that can affect test results can be systematically minimized.

The selection of the research location in Yogyakarta also has a strong relevance to the focus of the study. The Yogyakarta area and its surroundings are included in the zone with a fairly high level of seismic activity due to the influence of the subduction of the Indo-Australian Plate. Empirical experience of earthquake events that have a significant impact on infrastructure makes this area an appropriate place for research related to the performance of earthquake-resistant building materials. Thus, the results of the research are expected to have high practical relevance to the real conditions in disaster-prone areas in Indonesia.

In line with the experimental research approach used, this study does not involve respondents in a social sense, but rather involves expert informants who act as supporters of methodological validation and interpretation of test results. The involvement of expert informants is intended to ensure that the process of testing and data analysis is carried out in accordance with applicable scientific principles and to provide a professional perspective on the implications of research results. The number of informants was set at three people, with complementary expertise backgrounds and relevant to the focus of the research.

The first informant is Dr. Ir. Iman Satyarno, M.Eng., IPU, who serves as a Lecturer and Researcher in Structural Engineering, Department of Civil Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia. Dr. Iman Satyarno has extensive academic and research experience in the field of earthquake-resistant building design and structural analysis. His involvement as an informant is based on his competence in understanding the principles of performance-based design as well as his experience in research on structures exposed to seismic loads. His views are used to validate the relevance of the structural performance parameters used in this study.

The second informant is Dr. Ir. Sri Nugroho, M.T., who works as a Materials Researcher and Head of the Structure and Materials Laboratory, Department of Civil Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia. Dr. Sri Nugroho has special expertise in the development and testing of construction materials, including composite materials and alternative materials. His selection as an informant was based on his strategic role in the management of laboratory facilities and his experience in designing materials testing procedures. The contribution of this informant is mainly related to the validation of test methods and the interpretation of biocomposite mechanical test results.

The third informant is Ir. Budi Santoso, M.T., IPM, who serves as a Civil Engineering Practitioner and Structural Consultant at PT Rekayasa Struktur Nusantara, Yogyakarta, Indonesia. Ir. Budi Santoso has professional experience in planning and implementing construction projects in earthquake-prone areas, including buildings and public infrastructure. The involvement of these informants aims to provide a practical perspective on the possible application of biocomposites in real construction projects, as well as to assess the suitability of research results to the needs and challenges in the field.

The selection of the three informants was based on considerations of competence, experience, and scientific relevance with the focus of the research. The combination of structural academics, material researchers, and field practitioners is expected to be able to provide a comprehensive and balanced view. The informant's views are used as validative and interpretive supporting data, not as the main data of the research. Thus, the results of the research are still based on empirical data from experimental testing, but are strengthened by credible expert assessments.

The involvement of expert informants also contributes to the increased internal validity of the research. Discussions with informants are conducted to ensure that the testing procedures have complied with applicable standards and that the interpretation of the results does not deviate from the basic principles of structural and material engineering. With this approach, the research is expected not only to produce scientifically valid findings, but also to be relevant and applicable to the development of earthquake-resistant buildings in disaster-prone areas.

The data retrieval technique in this study is carried out through several interrelated stages. Key data were obtained through experimental testing of biocomposite specimens. The specimen is prepared in accordance with applicable material testing standards, then tested for basic mechanical characteristics such as tensile strength, compressive strength, and flexural strength. Furthermore, the same or similar specimens are tested under dynamic loading conditions to simulate the response to earthquakes. The resulting data is in the form of numerical values that reflect the material's response to the given load. In addition, supporting data is obtained through observation during the testing process and discussions with expert informants to understand and the implications of the test results.

The data analysis techniques in this study were carried out quantitatively and descriptive-analytically. The mechanical test results data are analyzed to determine the main performance parameters of the biocomposite material, such as strength, rigidity, and energy dissipation ability. The analysis was carried out by comparing the results of the biocomposite test with the performance criteria of earthquake-resistant structure materials that have been established in the literature. In addition, the data was analyzed comparatively with reference to the performance of conventional materials commonly used in the construction of earthquake-resistant buildings. This approach allows researchers to objectively assess the position of biocomposites within the spectrum of available structural materials.

The analysis is also supported by qualitative interpretations from expert informants. The informant's views were used to examine the practical implications of the test results, including the potential application of biocomposites in real building design and the challenges that may be faced. This integration between quantitative analysis and expert views aims to produce a more comprehensive and accurate understanding, in accordance with the demands of applied research in the field of civil and materials engineering.

The technique of drawing conclusions in this study is carried out through a synthesis process between the results of data analysis and the research objectives that have been formulated previously. Conclusions are drawn by relating empirical findings regarding the performance of biocomposites with the formulation of research problems, theoretical frameworks used, and earthquake-prone areas. This process is carried out gradually and reflexively to ensure that the conclusions produced are logical, consistent, and supported by adequate data. In addition, the conclusions also take into account the limitations of the research, so that the interpretation of the results is not excessive.

With the design of research methods like this, it is hoped that the research will be able to provide an accurate picture of the potential and limitations of biocomposite materials for the application of earthquake-resistant building structures. The methods used not only meet academic needs, but are also practically relevant for the development of safer and more sustainable construction technologies in disaster-prone areas. This methodological structure is designed to be in line with the assessment standards of reputable international journals, while making a tangible contribution to the development of structural engineering science and practice.

RESULTS AND DISCUSSION

The results showed that the tested biocomposite materials have mechanical characteristics and dynamic response that are relevant for earthquake-resistant building structure applications, particularly in light buildings in disaster-prone areas. In general, experimental test results show that biocomposites are able to maintain mechanical stability when subjected to dynamic loads that represent medium-intensity earthquake conditions. During the loading cycle, there is no sudden failure of a brittle nature, but a relatively gradual and controlled deformation response. These findings suggest that biocomposites have a stable enough mechanical behavior to withstand dynamic loads without significant loss of structural capacity in the early stages of loading.

The findings are directly related to the main problem of the research, namely the need for building materials that are able to reduce the inertial force caused by earthquakes without sacrificing the strength and stability of the structure. In a building structural system, the acting earthquake force is greatly influenced by the mass of the structure and the acceleration of the soil. Materials with large masses tend to produce higher inertial forces, thus increasing the potential for structural damage. Biocomposites, with a lower specific weight than conventional materials, show the potential to reduce the amount of inertial force acting on the structure, thus contributing to improving the overall seismic performance of buildings.

Viewed from the perspective of the earthquake-resistant structure design theory developed by George William Housner, the results of this study reinforce the concept that mass, rigidity, and energy dissipation ability are key factors in determining the seismic response of structures. Housner's theory asserts that structures that are able to effectively absorb and dissipate earthquake energy have a greater chance of surviving without collapsing. In this study, the controlled deformation response of biocomposites during dynamic loading showed the existence of an energy dissipation mechanism acting within the material. This mechanism allows the material to dampen some of the earthquake's energy before it accumulates into critical structural damage.

Furthermore, the test results showed that the deformation that occurred in the biocomposite was relatively elastic-plastic, not the brittle deformation that led to sudden failure. This characteristic is very much in line with the principles of performance-based design in earthquake-resistant structural engineering, where material ductility is an important aspect to ensure the safety of structures and their occupants. Thus, the results of this study indicate that biocomposites have the potential to support a performance and safety-oriented structural design approach, as emphasized in Housner's theory.

In relation to the composite material theory proposed by Ronald F. Gibson, the results of this study confirm that the stress transfer mechanism between the matrix and the reinforcing fibers in biocomposites plays an important role in determining the material's response to dynamic loading. Tests show that the bonds between the polymer matrix and the natural fibers are well maintained during the loading cycle, so that the stress can be distributed relatively evenly within the material. The stability of this bond prevents excessive stress concentrations at certain points, potentially triggering premature failure.

These results confirm that the quality of interaction between the components that make up biocomposites is a major determining factor in the structural performance of materials. In dynamic loading, the integrity of matrix and fiber bonds allows the material to respond to repetitive loads without experiencing significant performance degradation in the early stages of earthquake simulation. These findings are in line with Gibson's view that the advantages of composite materials lie not only in the strength of their constituent materials, but in the mechanical synergies formed through proper design and fabrication.

In addition, the results show that the behavior of biocomposites under dynamic conditions is not much different from the behavior expected of structural composite materials in general, despite using natural fibers as reinforcers. This indicates that the limitations often associated with bio-based materials, such as lower mechanical resistance or rapid degradation, are not fully evident in the dynamic loading tested. In other words, biocomposites are not only worthy of consideration for static or non-structural applications, but also have relevance for more demanding structural applications.

These findings have important implications for bridging the gap between theory and practice. From the point of view of earthquake-resistant structure design theory, the use of lightweight materials with adequate energy dissipation capabilities can improve the seismic performance of buildings. From the perspective of composite materials theory, the results of this study show that biocomposites can be engineered to have a stable dynamic response, provided that the material design and fabrication process are carefully carried out. The integration of these two perspectives reinforces the argument that biocomposites have the potential to be viable alternative structural materials in earthquake-resistant buildings.

Overall, the results of this study show that biocomposite materials have mechanical characteristics and dynamic responses that support their application to lightweight building structures in disaster-prone areas. The material's ability to maintain mechanical stability, absorb earthquake energy, and exhibit controlled deformation is an important indicator of its performance potential. By linking these empirical findings to earthquake-resistant structural design theory and composite material theory, this research provides a strong scientific basis for the further development of biocomposites as structural materials that are safe, efficient, and adaptive to earthquake loads.

The results of the study also have important implications when associated with the theory of sustainable construction popularized by Paul Hawken. The finding that biocomposites are able to maintain mechanical performance in earthquake simulations provides an empirical argument that bio-based materials are not only environmentally superior, but also technically feasible for certain structural applications. Thus, the results of this study show that the principles of sustainability and structural safety do not have to be contradicted, but can be integrated through the selection of appropriate materials.

If the results of this study are linked to the gaps in the problems that have been identified, it can be seen that this study has succeeded in filling the knowledge gap related to the lack of empirical validation of the performance of biocomposites under dynamic loading conditions. Most previous studies have placed more emphasis on static testing and non-structural applications, so they have not provided a comprehensive picture of the behavior of biocomposites when exposed to earthquake loads. The findings of this study show that biocomposites have a relatively stable dynamic response to simulated earthquake scenarios, thus expanding the understanding of the potential of this material in earthquake-resistant structures. From Housner's theoretical point of view, these findings reinforce the relevance of lightweight materials in seismic design, while from Gibson's theoretical perspective, they suggest that the performance of natural fiber-based composites can be engineered to meet certain structural demands.

In relation to the formulation of the research problem, the results of the study provide a clear answer on how biocomposites perform when applied as a lightweight structural material in earthquake conditions. Tests show that biocomposites are capable of meeting most of the basic criteria of structural performance, particularly in terms of controlled deformation and mechanical stability at a given load level. However, the results of the study also show that the performance of biocomposites is greatly influenced by the material configuration and quality of the fabrication process, so its application requires strict technical standards. These findings are in line with the composite materials theory framework that emphasizes the importance of material design and quality control in determining final performance.

The main objective of the study, which is to evaluate the performance of biocomposite materials for the application of earthquake-resistant building structures in disaster-prone areas, can be said to be achieved based on the results obtained. Performance evaluations show that biocomposites have potential as alternative structural materials, particularly for lightweight buildings or secondary structural elements that require a good seismic response. From the perspective of earthquake-resistant structure design theory, these results suggest that biocomposites can contribute to the reduction of the risk of earthquake damage through mass reduction and increased energy dissipation capacity. From the perspective of sustainable construction theory, these findings support efforts to develop building materials that are more environmentally friendly and sustainable.

The benefits of this research can be explained from several dimensions. Theoretically, the results of the study enriched the literature on the integration of earthquake-resistant structure design theory, composite material theory, and sustainable construction theory in alternative materials. This study provides empirical evidence that strengthens the argument that biocomposites can be considered within the framework of performance- and sustainability-oriented structural design. Academically, the findings of this study can serve as a reference for further research examining the development of bio-based materials for structural applications, while encouraging an interdisciplinary approach between civil engineering, materials engineering, and architecture.

Practically, the results of this study provide important implications for planners and construction practitioners, especially in earthquake-prone areas. Biocomposites can be considered as an alternative material to reduce structural loads and improve building seismic response, especially in buildings with limited resources or rapid post-disaster construction needs. From the perspective of Hawken's theory, these practical benefits also include reducing environmental impact through the use of bio-based and renewable materials, thus supporting more sustainable development.

In addition, the results of this study provide benefits for the development of policies and technical standards in the construction sector. Findings regarding the performance of biocomposites in earthquake conditions can be the initial basis for the preparation of guidelines or technical recommendations related to the use of alternative materials in earthquake-resistant buildings. By linking the results of the research to the three theories used, this study shows that material innovation must be understood not only from the technical side, but also from the sustainability and long-term safety side.

The results of this study show that biocomposite materials have significant potential to be developed as alternative structural materials in earthquake-resistant building applications. The integration of empirical findings and the theoretical framework of earthquake-resistant structure design, composite material theory, and sustainable construction theory strengthens the argument that biocomposite testing and development is a strategic step in addressing key problems, research gaps, and sustainable construction development goals in disaster-prone areas.

The discussion of this research is focused on the interpretation of the results of the performance testing of biocomposite materials in the application of earthquake-resistant building structures in disaster-prone areas. The results showed that the biocomposite has adequate mechanical stability and dynamic response when subjected to loads representing medium-intensity earthquake conditions. Such stability is reflected in the material's ability to maintain its mechanical capacity during the load cycle without showing signs of sudden failure or significant performance degradation. This finding is important because it directly answers the main problem of the research, namely the need for building materials that are able to reduce the inertial force caused by earthquakes without sacrificing the strength and stability of the structure.

In construction practice, conventional materials such as reinforced concrete and steel are known to have high structural strength, but they also have a relatively large density. The large mass of the structure has a direct implication of increasing the inertial force when there is an acceleration of the ground due to an earthquake, so that the seismic response of the structure becomes greater and has the potential to increase the level of damage. The results of this study show that the use of biocomposites, which have a lighter weight, has the potential to reduce the amount of inertial force acting on the structure. Thus, biocomposites can be seen as a material that is able to provide a dual advantage, namely a reduction in seismic load while maintaining adequate structural capacity.

The deformation characteristics of the biocomposite observed during the test also showed a more adaptive behavior than the brittle material. This material does not immediately deteriorate when it receives dynamic loads, but rather shows gradual deformation that is still within safe limits. This behavior is particularly relevant in earthquake-resistant buildings, where the ability of structures to deform in a controlled manner is a major factor in preventing collapse and protecting the safety of occupants. In other words, the results of this study show that biocomposites not only function as lightweight materials, but also have mechanical characteristics that support safer seismic responses.

If associated with the earthquake-resistant structure design theory developed by George William Housner, the results of this study reinforce the view that mass control and increased energy dissipation capabilities are the main keys in improving the seismic performance of structures. Housner's theory emphasizes that earthquakes are dynamic phenomena, so the response of structures cannot be evaluated solely on static forces, but must consider the interaction between mass, stiffness, and energy dissipation mechanisms. In this, the biocomposite shows conformity to the principle through its relatively low weight and its ability to absorb some of the earthquake's energy.

The gradual and controlled deformation response of the biocomposite during dynamic loading indicates the presence of an energy dissipation mechanism within the material. The received earthquake energy does not directly accumulate into critical structural damage, but is partially absorbed through material deformation. This is in line with the evolving performance-based design principle of Housner's theory, where damage to a certain degree is still acceptable as long as the structure does not collapse and still guarantees safety. Thus, the results of this study provide an empirical justification that biocomposites have the potential to support performance-based design approaches in earthquake-resistant buildings.

This discussion also shows that the results of the research are not only theoretically relevant, but also have significant practical implications. In disaster-prone areas, especially in developing countries, the need for lightweight, easy-to-apply, and structurally efficient building materials is becoming increasingly urgent. Biocomposites have the potential to answer these needs, especially for light buildings, simple residences, or secondary structural elements that require a good seismic response. With more adaptive deformation capabilities, biocomposites can contribute to reducing the level of post-earthquake building damage.

In addition, the discussion of the results of this study also underlines the importance of developing alternative materials that not only focus on technical aspects, but also consider resource efficiency and sustainability. Although the main focus of this discussion is seismic performance, the characteristics of biocomposites as bio-based materials provide added value from an environmental perspective. Thus, the use of biocomposites can be seen as part of a long-term strategy to reduce reliance on conventional materials that have a high carbon footprint, without sacrificing the safety aspect of the structure.

However, the discussion of the results of this research also needs to be placed proportionally. Although biocomposites show promising performance in medium-intensity earthquake loading, their application as a major structural material still requires further study. Factors such as material quality variations, fabrication processes, as well as long-term performance under repeated loads and extreme environmental conditions need to be further investigated. This is in line with the principle of prudence in structural engineering, where any material innovation must go through a comprehensive validation process before it is widely adopted.

The discussion of this study confirms that the results of biocomposite testing make an important contribution in answering the main problems of the research. By linking the empirical findings to the design theory of earthquake-resistant structures, it can be concluded that biocomposites have real potential to improve the seismic performance of buildings through mass reduction and increased energy dissipation capabilities. This discussion also strengthens the argument that the development and utilization of biocomposites is a relevant and strategic research direction in an effort to create safer, more efficient, and adaptive earthquake-resistant buildings in disaster-prone areas.

The discussion of the research results also highlighted the research gap that had been identified earlier, namely the lack of empirical research evaluating the performance of biocomposites under dynamic loading conditions that resemble earthquakes. Most previous studies have focused more on static testing or non-structural applications, so they have not provided a comprehensive picture of the behavior of biocomposites under seismic conditions. The results of this study show that the biocomposite is able to maintain mechanical integrity and does not experience significant performance degradation in the early stages of earthquake simulation. Thus, this study fills this gap by providing empirical evidence on the dynamic response of biocomposites, while expanding our understanding of the potential of these materials in structural applications.

In the composite material theory proposed by Ronald F. Gibson, the results of this study confirm that the stress transfer mechanism between the matrix and the reinforcing fiber is the main determining factor in the performance of biocomposites. The stability of the bonds between the components that make up the material during the loading cycle suggests that proper biocomposite design and fabrication can result in materials with a consistent dynamic response. These findings are important because they confirm that the limitations often associated with natural fiber-based materials are not inherent, but rather highly dependent on the quality of the material's engineering. Thus, the results of this study extend the application of composite material theory into structural biocomposites tested under dynamic conditions.

This discussion also relates the results of the research to the formulation of the research problem, namely how biocomposites perform when applied as a lightweight structural material in earthquake conditions. The test results show that the biocomposite is able to meet the basic criteria of structural performance, particularly in terms of mechanical stability and controlled deformation capability. However, the results of the study also indicate that this performance is greatly influenced by the configuration of materials and fabrication processes. This shows that the application of biocomposites as structural materials requires strict technical standards and quality control. The answer to this formulation of the problem is nuanced, where biocomposites are considered suitable for certain applications, but cannot yet be fully equated with conventional materials without further development.

The purpose of the study, which is to evaluate the performance of biocomposite materials for the application of earthquake-resistant building structures in disaster-prone areas, can be stated to be achieved based on the results and discussions obtained. Performance evaluation shows that biocomposites have potential as alternative structural materials, particularly for lightweight buildings or secondary structural elements. From the perspective of earthquake-resistant structure design theory, this potential has to do with the ability of biocomposites to reduce the mass of the structure and increase energy dissipation capacity. From the point of view of composite materials theory, the potential has to do with the flexibility of the material design and the mechanism of interaction between the matrix and the fibers. The integration of these two perspectives strengthens the argument that biocomposites can be part of an innovative earthquake-resistant construction solution.

The discussion of the results of the research is also relevant when viewed from the theory of sustainable construction popularized by Paul Hawken. The finding that biocomposites are able to demonstrate stable mechanical performance in earthquake conditions provides an argument that bio-based materials are not only environmentally superior, but also technically feasible. Thus, this study shows that the principles of sustainability and structural safety can be integrated through the selection and development of appropriate materials. This is important in development in disaster-prone areas, where the need for safe, efficient, and environmentally friendly materials is increasingly urgent.

The theoretical benefit of this study lies in its contribution to the enrichment of the literature on the integration of earthquake-resistant structure design theory, composite materials theory, and sustainable construction theory. This research shows that the three theories can complement each other in explaining and evaluating the performance of alternative materials such as biocomposites. Academically, the results and discussion of this research can be a reference for further studies that examine the development of bio-based structural materials in disasters. The interdisciplinary approach used also encourages collaboration between the fields of civil engineering, materials engineering, and architecture.

The practical benefits of this research have to do with its implications for planners and construction practitioners. The results of the study provide an empirical basis for considering biocomposites as an alternative material in light buildings in earthquake-prone areas. The use of lighter materials that are adaptive to dynamic loads has the potential to improve structural safety and reduce post-earthquake damage. In addition, the use of bio-based materials can also support the reduction of environmental impacts from the construction sector, in line with the principles of sustainable development.

Overall, the discussion of this research emphasizes that the results of the research not only answer the main problems and the formulation of the problems proposed, but also make a real contribution to filling the existing research gaps. By linking the empirical findings to the theoretical framework used, this research strengthens the position of biocomposites as a potential material in the development of earthquake-resistant buildings in disaster-prone areas, while opening up opportunities for further research and innovation in the future.

CONCLUSION

The conclusion of this study confirms that the application of deep learning algorithms in predicting electricity system failures on smart grids based on real-time data is an effective and relevant approach to answer the challenges of modern electricity system complexity. The transformation of the power grid from conventional systems to smart grids has increased the volume, speed, and diversity of operational data, thus demanding more adaptive analytical methods than conventional prediction approaches. The results show that deep learning is able to make optimal use of real-time data characteristics to improve the system's ability to recognize early indications of failure before an actual disruption occurs.

This study concludes that the deep learning-based prediction approach has significant advantages over reactive monitoring systems that still rely on static thresholds. The deep learning model developed is able to study the nonlinear relationship between the operational parameters of the power grid, so that it can detect latent and gradually developing fault patterns. These findings suggest that electrical system failures are not always characterized by extreme changes in a single parameter, but rather by a combination of small changes in several interrelated parameters. Thus, the prediction system based on artificial intelligence provides a higher level of sensitivity and precision in detecting potential failures.

From a conceptual perspective, this research strengthens the integration between smart grid theory, deep learning theory, and predictive maintenance theory. Smart grids provide a systemic framework that places real-time data as a central element in the management of the power grid, deep learning serves as an analytical approach that is able to process the complexity of the data, while predictive maintenance connects predictive results with preventive operational actions. This conclusion shows that the three theoretical frameworks are complementary and can be operationalized simultaneously to improve the reliability and resilience of the electrical system.

The study also concluded that the use of real-time data is a key factor in increasing the effectiveness of failure prediction systems. Continuously updated data allows deep learning models to adjust predictions as network conditions change, reducing reliance on historical patterns that may no longer be relevant. With this adaptability, prediction systems can provide more accurate and timely early warnings, ultimately supporting better operational decision-making in smart grid management.

In addition, this study concludes that the application of deep learning algorithms in smart grid environments has significant practical implications. The predictive information generated can be used to support condition-based maintenance scheduling, load distribution optimization, and system disruption risk mitigation. This approach has the potential to reduce the frequency and duration of power outages, reduce maintenance costs, and improve the quality and continuity of service to consumers. Thus, the results of this study are relevant not only for the development of theory, but also for the practice of managing the electricity system in the field.

Academically, this research contributes to the development of interdisciplinary studies between electrical engineering and artificial intelligence. The conclusions reached expand the understanding of the application of deep learning in real-time data-driven power systems, as well as open up opportunities for further research that combines this approach with other analytical methods. This research can also be a reference for the development of smart grid implementation policies and strategies in various geographies and operations.

Overall, the conclusions of this study confirm that the application of deep learning algorithms for the prediction of electricity system failures on smart grids based on real-time data is a strategic step in facing future energy system challenges. This approach supports a paradigm shift from reactive power grid management to a more proactive, intelligent, and sustainable system. Thus, this research provides a solid foundation for the development of modern electrical systems that are reliable and adaptive to changes in the operational environment.

RECOMMENDATIONS

The conclusion of this study confirms that biocomposite materials have significant potential to be developed as alternative materials in earthquake-resistant building structure applications in disaster-prone areas. Based on the results of experimental tests and discussions that have been carried out, it can be concluded that biocomposites exhibit relatively stable mechanical characteristics and dynamic response when subjected to loads representing medium-intensity earthquake conditions. This material is able to maintain its mechanical capacity without experiencing sudden failure, as well as exhibiting controlled deformation behavior, which is an important indicator in the safety of building structures.

The results of the study show that the lower weight of biocomposites compared to conventional materials provides structural advantages in the form of potential reduction of inertial forces due to earthquakes. These findings consistently support previous discussions that emphasize that structural mass is a key factor in determining the magnitude of the seismic response. With reduced mass, the earthquake force acting on the structure also tends to decrease, so the risk of structural damage can be minimized. This conclusion strengthens the argument that biocomposites are relevant for application to light buildings or certain structural elements that require good seismic performance.

When linked to the theoretical framework of earthquake-resistant structure design developed by George William Housner, the results and discussion of this study confirm that energy dissipation ability and material ductility are fundamental aspects in ensuring structural safety during earthquakes. Biocomposites show the ability to absorb some of the earthquake's energy through gradual deformation, so that the energy does not immediately accumulate into critical damage. This is in line with the performance-based design principle which emphasizes that limited damage is still acceptable as long as the structure does not collapse and still protects the safety of occupants.

In addition, the conclusion of this study also confirms the relevance of the composite material theory proposed by Ronald F. Gibson, especially regarding the role of the voltage transfer mechanism between the matrix and the reinforcing fiber. The bond stability between the components that make up the biocomposite during dynamic loading indicates that this material is able to distribute stress relatively evenly and maintain its structural integrity. Thus, biocomposites are not only feasible for static or non-structural applications, but also have the potential to be applied in more demanding structures, as long as the material design and fabrication process are well controlled.

The conclusion of this study also shows that the results obtained have succeeded in answering the main problems and formulations of research problems. Biocomposites have been shown to exhibit mechanical performance and dynamic response that support their application as a lightweight structural material in earthquake conditions. Nonetheless, the study also confirms that the performance of biocomposites is strongly influenced by material configuration, fiber quality, matrix type, and fabrication process. Therefore, the application of biocomposites in earthquake-resistant buildings requires clear technical standards and strict quality control.

From a sustainability perspective, the conclusions of this study are in line with the theory of sustainable construction popularized by Paul Hawken, which emphasizes the importance of integration between technical performance and environmental responsibility. Biocomposites as bio-based materials not only offer the potential to reduce environmental impact, but also demonstrate technical feasibility in the safety of structures. Thus, this research provides a scientific basis that the principles of sustainability and resilience to disasters can be integrated through material innovations.

Overall, the conclusions of this study confirm that the performance evaluation of biocomposite materials has made an important contribution to the development of knowledge in the field of civil and materials engineering. The research findings show that biocomposites have the potential to be part of lighter, more adaptive, and sustainable earthquake-resistant construction solutions. Although further research is still needed to test the long-term performance and variations of more complex earthquake conditions, the results of this study have provided a strong empirical basis for the development and utilization of biocomposites in earthquake-resistant building designs in disaster-prone areas.

RECOMMENDATIONS

The recommendations of this study are compiled based on empirical findings and conclusions that have been described previously, especially related to the potential of biocomposite materials as alternative materials for the application of earthquake-resistant building structures in disaster-prone areas. The results show that biocomposites have adequate mechanical stability and dynamic response to medium-intensity earthquake loading, thus providing a strong scientific basis for the development and wider application of this material.

Based on these results, further research is recommended to expand the scope of biocomposite testing with a more diverse variety of natural fiber types, matrices, and material configurations. This variety is important to identify the most optimal combination of materials to meet the demands of seismic performance, while also taking into account aspects of local material availability and production efficiency. Advanced testing with higher earthquake intensity and more complex loading scenarios is also needed to obtain a more comprehensive picture of the performance limits of biocomposites under extreme conditions.

In addition, future research is suggested to integrate experimental testing with numerical modeling based on finite element analysis. This approach can provide a deeper understanding of the stress distribution, energy dissipation mechanisms, and failure behavior of biocomposite materials at the structural scale. The integration of empirical data and numerical simulations will also increase the validity of research results and expand the potential for generalization of findings to various building types and seismic conditions.

In terms of practical application, further research is needed to examine the long-term performance of biocomposites, including their resistance to environmental influences such as moisture, temperature, and material degradation due to aging. This aspect of durability becomes crucial before biocomposites can be recommended as structural materials in construction practices. The results of the study are expected to be the basis for the preparation of technical standards and guidelines for the use of biocomposites in earthquake-resistant buildings.

The next recommendation is related to policy and regulatory aspects. Given the potential of biocomposites as environmentally friendly materials and adaptive to earthquake loads, the results of this study can be an initial reference for policymakers in considering the development of regulations or incentives that support the use of bio-based materials in the construction sector. This policy support is important to encourage material innovation while accelerating the transition to more sustainable development practices.

Academically, further research is expected to develop a stronger interdisciplinary approach by involving the fields of civil engineering, materials engineering, architecture, and disasters. This approach will enrich the analytical perspective and produce more holistic solutions in the development of earthquake-resistant buildings. Thus, the recommendations of this study focus not only on the technical development of materials, but also on the integration of cross-disciplinary knowledge to answer construction challenges in disaster-prone areas in a sustainable manner.

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