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Bridging Knowledge Gaps in Bamboo Construction for Scalable Housing through the Base Innovation Center

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Abstract

Base Bahay Foundation, Inc. (BASE), initiated by the Hilti Foundation in the Philippines, established the Base Innovation Center (BIC) as the research hub for bamboo construction and to fill in the knowledge gaps for scalable bamboo housing construction. The utilization of bamboo as construction material requires an in-depth understanding of the behavior of bamboo. Different testing methods are used to provide an engineering basis for the construction of housing made using bamboo. Most of the research and scientific data is gathered through partnerships with academic universities and research institutions. This paper provides an overview of the ongoing research initiatives at BIC and shows future research agendas.

Keywords Bamboo; BASE; BIC; Innovation; Research hub

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1. Introduction

Almost 19% of the world's emissions of greenhouse gases are generated by the construction industry (Labaran et al. 2021). The use of alternative materials that can lower overall carbon emissions including the use of materials that can be produced from natural and renewable resources such as plants is being explored. One of which is bamboo, a fast-growing plant from the grass *Poaceae* family, which not only can be durable but is a good carbon sequester (Seethalakshmi et al. 2009). Bamboo has been used by many people around the world, as their main construction material.

Bamboo has been used for hundreds of years in traditional construction and vernacular houses. One of the usual construction methodologies for vertical structures using bamboo in sub-tropical areas is the *Bahareque encementado* (Lopez et al. 2015). This methodology uses bamboo as the main structural component while using cement plaster to protect the bamboo from direct weather. However, it only has 30 years wherein it has been properly documented and studied. In this regard, very little is documented in terms of research and structural design for this material. Several topics still need to be studied as shown in the study by Harries (2022). The answers to some of the most common connections used in construction still need to be researched. Alongside that, very few of the bamboo species have been properly characterized. With only 4 to 5 species including *Guadua angustifolia*, *Dendrocalamus asper*, and *Bambusa blumeana*, several species can be found all over the world that may be structural grade. This raises a potential interest in developing Bamboo as a sustainable construction material.

Bamboo gained the interest of most builders around the tropical countries with abundant resources of usable bamboo. Prioritizing research regarding the use of bamboo and the behavior of their physical properties subjected to stresses is being prioritized. Limited publication of scientific and practical references concerning bamboo's structural properties and behavior slows the acceptance of the utilization of bamboo as an alternative construction material. The International Organization for Standardization (ISO) Technical Committee 165 published several standards regarding the determination of characteristic values for the mechanical strengths of bamboo culms (ISO 12122-1), their physical and mechanical properties (ISO 22157:2019), and the latest publication of bamboo structural design (ISO 22156:2021).

With proper research and development approaches, advancing the bamboo structural design can be achieved. This paper shows how the Base Bahay Foundation, Inc. (BASE), through its Base Innovation Center (BIC), answers the call for in-depth research on bamboo as a structural component and a sustainable construction material.

1.1 Base Bahay Foundation, Inc.

One of the largest concerns happening in the world is the lack of adequate housing. In the Philippines, as found right beside the Pacific Ocean, an annual average of 20 typhoons hit the country destroying Filipino houses. The gap in providing alternative materials to come up with more affordable and sustainable socialized housing came as a research goal and must be addressed.

The Hilti Foundation initiated Base Bahay Foundation, Inc. (BASE) in the Philippines which provides alternative building technologies by making bamboo the main material to build quality socialized housing as shown in Fig. 1. The research initiative of BASE started from an innovation for low-rise construction in the urban tropics that uses bamboo as a structural element for cost-efficient housing in 2011 (Salzar 2015). In the study of Salzer (2018), it was found that the possible solution to low-cost housing while also a good material to reduce carbon emissions is Bamboo. The BASE also partners with other organizations and institutions with the same level of advocacy and dedication in providing for the needs of other people. To name a few, partners including Don Antonio O. Floirendo, Sr. Foundation, Inc. (AOFF), Ayala Land Inc., and Habitat for Humanity Philippines provide socialized housing for different sectors. Notable projects include the Negros Occidental Impact 2025 (NOI25) of Habitat for Humanity which provided hundreds of houses in the western Visayas region of the Philippines.

Fig. 1. Affordable mass housing for communities in Negros Occidental (BASE).

With this research initiative, the Hilti Foundation saw a huge potential for bamboo and decided to keep BASE as the focal point that develops these technologies through the help of its research hub, the Base Innovation Center (BIC), where they conduct research and testing programs, as well as training courses in partnership with institutions and professionals on alternative building technologies. Shown in Fig. 2 is one of the strongholds that the BIC continues to develop, is the bahareque-inspired composite bamboo shear wall also known as cement-bamboo frame in the Philippines. This technology is being used by BASE to support their main mission of providing housing that is comfortable, affordable, yet disaster-resilient and made of environmentally friendly materials. This helps the foundation hold firm to its advocacy regarding a lower carbon footprint in the construction of socialized housing for marginalized communities.

Fig. 2. Cement-bamboo frame technology (CBFT), Negros Occidental.

This technology also piqued the interest of BASE’s international partners in Nepal and India. Through Habitat for Humanity Nepal, the CBFT was brought to the country of Nepal and has been able to build over 400 houses since 2020. The BASE supports its international partner by providing technical expertise and relevant training in harvesting, handling, treating, and building using bamboo. The technology offered also promotes gender equality in construction as the knowledge transfer made is applicable to provide livelihood to all available workforce in the community as shown in Fig. 3. With its modular approach, prefabricated CBFT walls can also improve the productivity of construction without compromising the quality of the bamboo housing.

(**a**) (**b**)

Fig. 3. CBFT construction in Nepal: (a) typical construction methodology; (b) Prefabricated CBFT construction.

1.2. BASE Innovation Center

With the promising performance and effectiveness of the composite bamboo shear wall (CBSW) technology of BASE in the form of Cement-Bamboo Frame Technology (CBFT) walls, the continuous usage of bamboo through the years led to the initialization of the Base Innovation Center (BIC) in 2020. There is a strong demand for research and development to provide guiding principles and a basis for engineering design for the utilization of CBFT in housing. Along with the strong partnership with different research-oriented universities, the BIC is a knowledge center wherein students and researchers can collaborate, as shown in Fig. 4.

Fig. 4. Base Innovation Center, Makati, Philippines.

The BASE, with the help of its BIC, was able to characterize one of the most common bamboo species used as a construction material in the Philippines, *Bambusa blumeana,* locally known as Kawayan Tinik. They are completing the data to fully understand the said species and are now doing various tests on different species available for construction use.

1.2.1. *Partner Universities and Other Organizations*

With the emerging topic of usable bamboo in construction, the demand for usable data for analysis also increases. This increase in interest influenced the demand for more manpower. The BIC, with its growing capacity, invites local and international research-oriented universities to send their students, both undergraduate and graduate students, to participate and do their dissertations in BIC. Shown in Table 1 and Table 2 are the partner universities actively sending students to research and study more about bamboo and its behavior.

Table 1. List of local partner universities for bamboo research.

Philippine Universities	Location
De La Salle University – Manila (DLSU)	Manila
University of the Philippines – Diliman (UPD)	Quezon City
University of Santo Tomas (UST)	Manila
Mapua University (MU)	Manila
Polytechnic University of the Philippines (PUP)	Manila
Foundation University	Dumaguete, Negros Oriental
Technological University of the Philippines (TUP)	Manila

Table 2. List of international universities for bamboo research.

International Universities	Location
Coventry University	Great Britain
ETH Zürich	Switzerland
University of Pittsburgh	USA
Universidad del Valle	Colombia
Hong Kong University of Science and Technology	Hong Kong
Universiti Teknologi Mara	Malaysia
Virginia Tech	USA
Los Andes university	Colombia
Hong Kong University	Hong Kong

Table 3. List of other partnerships.

Institution	Location
International Bamboo and Rattan Organization (INBAR)	China
Arup	United Kingdom
Incon.AI	Switzerland
Terwilliger Center for Innovation in Shelter	Atlanta, Georgia
Kawayan Collective	Dauin, Philippines
Kanya Kawayan	Batangas, Philippines
Don Antonio O. Floreindo, Sr. (AOF) Foundation	Panabo, Davao

BASE is also collaborating with other organizations and leading institutions for bamboo and structural engineering for common research agendas and project initiatives. Shown in Table 3 are different organizations that have ongoing project initiatives, including incremental building and alternative building materials made of bamboo.

Along with the utilization of the testing equipment, the BIC also offers proactive participation in data gathering, data analysis, and interpretation of results, not only for the students to finish their requirements in their respective institutions but also for a uniform presentation of results. Shown in Fig. 5 is the trend of the number of students per year who had completed testing and their studies about bamboo with the help of BIC. The BIC has already been able to accommodate about 97 students with 35 research topics, focusing on the characterization of bamboo species and testing of connections and walls.

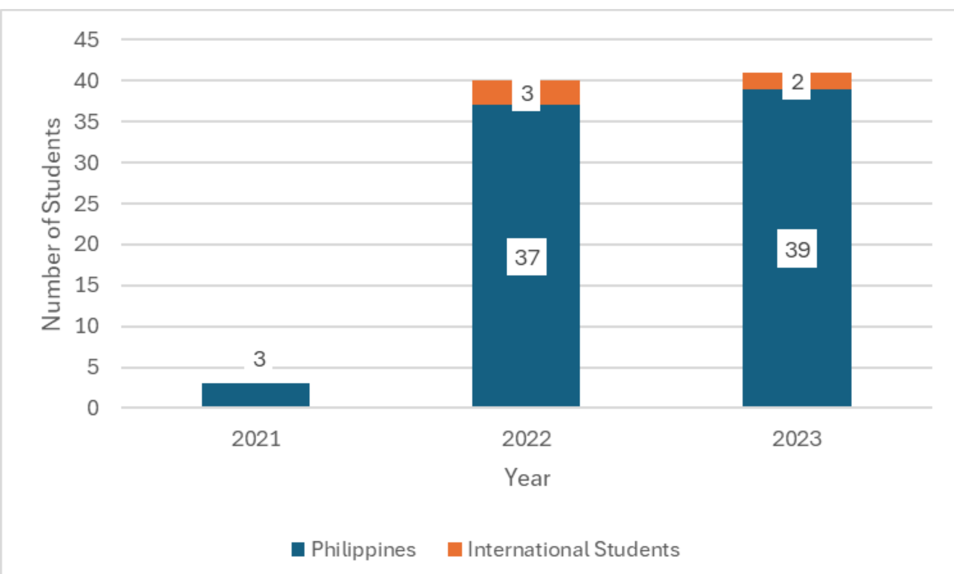


Fig. 5. Number of students who attended BIC per year.

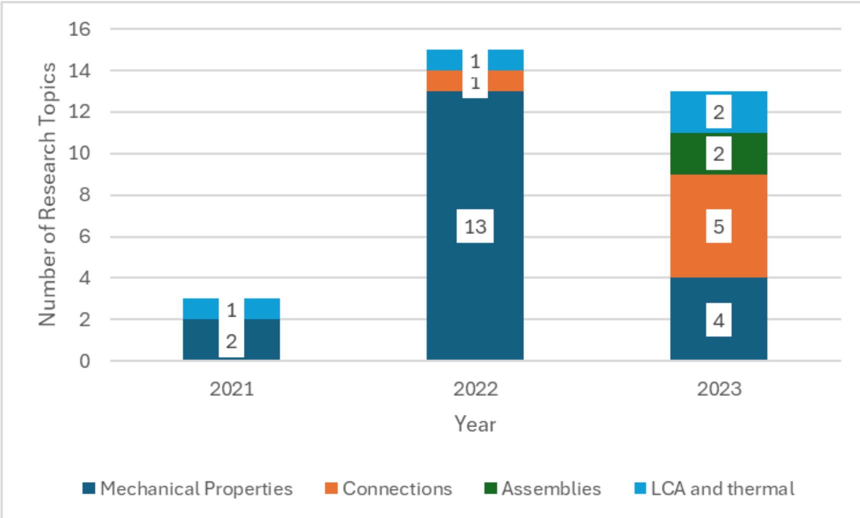


Fig. 6. Number of research topics per category per year.

Shown in Fig. 6 is the trend of research topics done in the BIC for the past years. We can subdivide the research topics into four main groups: (1) the properties of each bamboo culm; (2) the strength and behavior of connections; (3) the performance of assemblies and walls, and; (4) the Life Cycle Assessment (LCA) and thermal comfort studies.

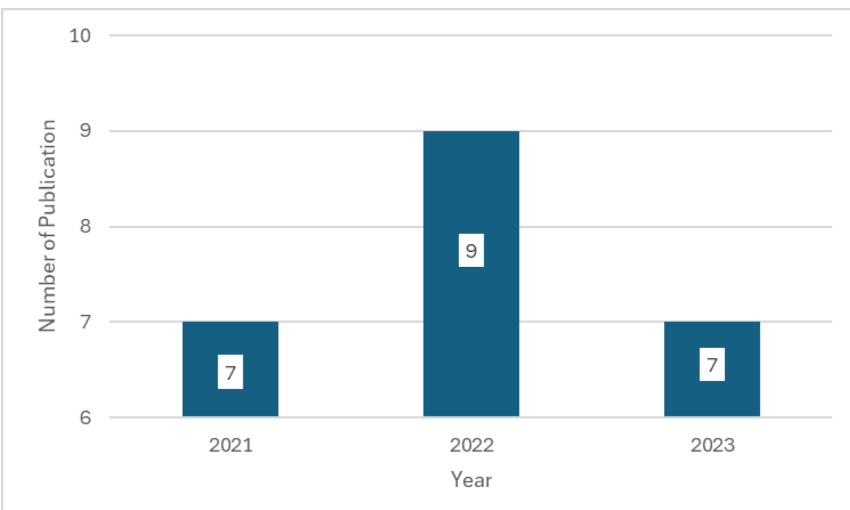
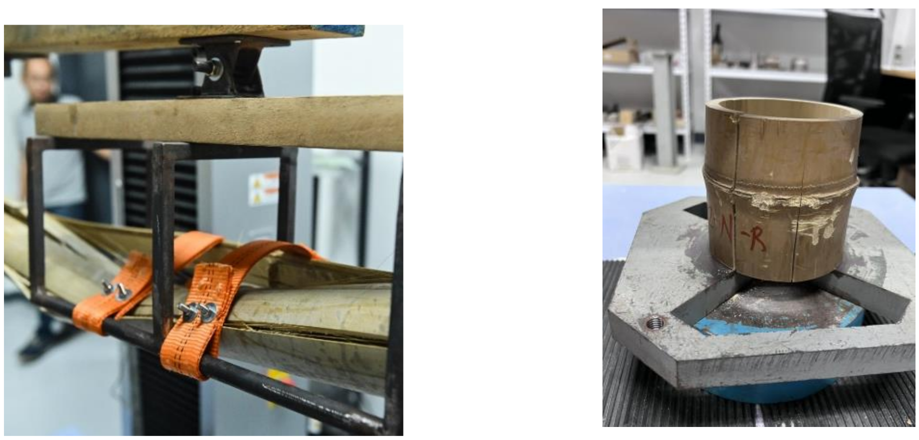


Fig. 7. Number of Publications per year.

We can observe that for the years 2021 and 2022, the conducted research is focused mainly on the characterization of the mechanical properties of bamboo materials, specifically *Bambusa blumeana*. After having an ample amount of data that can be used to understand the behavior of bamboo, the testing for mechanical connections and different connections of bamboo started in the last quarter of 2022. The number of research topics regarding connections went high in quantity for the succeeding years. The rise in the number of tests on connections includes the dowel connection from the foundation to the bamboo, a new method of foundation connection in the form of straps, and tests on T-connection. As the capacity to handle testing of BIC improves, with the addition of a reaction frame in the list of the testing equipment, the BIC was able to start testing full-scale and large assemblies of walls, testing about twenty (20) 2.4 m x 2.4 m wall panels in 2023. Shown in Fig. 7 is the number of publications made through these partnerships per year.

1.2.2. Testing for mechanical properties of bamboo

To provide the basis of engineering design, the characteristic values for the various mechanical properties of Bamboo should be studied. As one of the pillars of research, the fundamentals of the mechanical properties are studied per species. The testing standard for this is through the ISO 22157 ~ Bamboo Structures: Testing methods on the physical and mechanical properties of Bamboo.



(a) **(b)**

Fig. 8. Sample testing of bamboo: (a) bending test; (b) Shear test.

Notable studies include the comparative analysis of the shear strength of the different local bamboo species in the Philippines where the force is applied parallel to the fiber as shown in Fig. 8b. Bautista et al. (2021) presented the results showed that *Bambusa blumeana* has the highest average shear strength, followed by *Gigantochloa apus*, *Dendrocalamus asper*, *Bambusa philippinensis*, and *Bambusa vulgaris*. Shown in Fig. 9 is the average shear strength of different species parallel to fibers (f_v). It was observed that *Bambusa blumeana* has the highest average shear strength compared to the other four species but also showed the highest coefficient of variance (COV) at 27.8%. The study also showed that the presence of internodes in shear strength testing parallel to fibers does not represent a statistically significant difference compared to specimens without internodes.

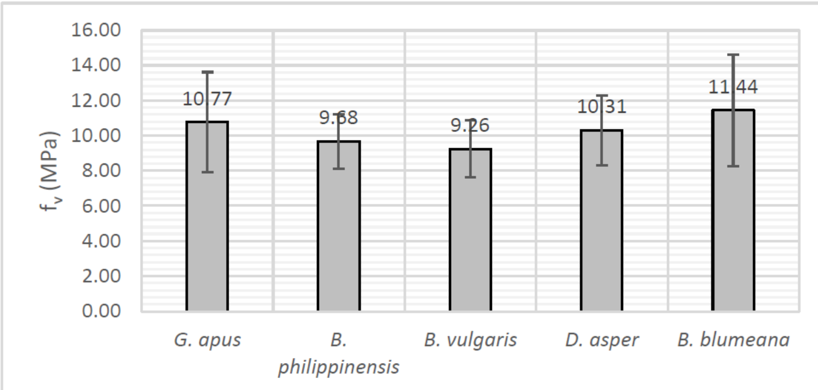


Fig. 9. Average shear strength parallel to fiber (f_v) (Bautista et al. 2021).

The characteristic shear strength parallel to fiber for the tested bamboo species is shown in Fig. 10.

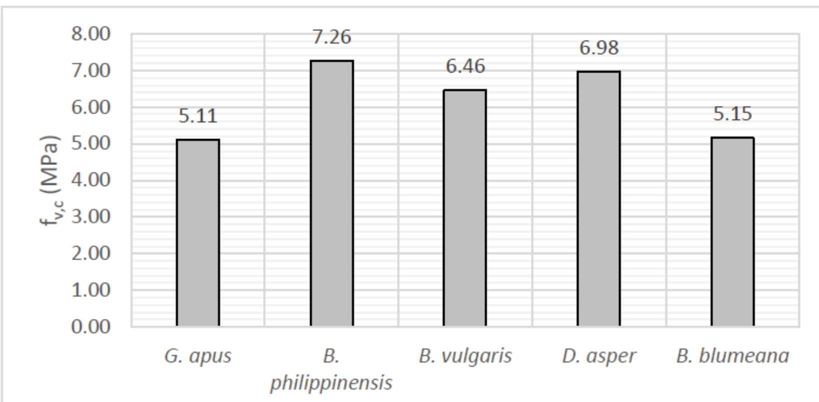


Fig. 10. Characteristic shear strength parallel to fiber ($f_{v,c}$) (Bautista et al. 2021).

It can be observed that the specimen with high COV has a lower characteristic value, as the characterization of strength considers ranking and does not eliminate the low shear strength values obtained in the testing. Thus, any low strength values pull down the resulting characteristic value of that data set.

1.2.3. Testing for connections

To understand further the behavior of bamboo, testing on assembled connections is being explored. From the current projects of the Base Innovation Center, the most common dowel foundation connection is being researched. This is the presence of the steel dowel inside of the bamboo and the placement of a mortar infill inside to allow bonding between the two materials. BASE is currently checking the strength of this connection alongside the added strength with the presence of steel clamps as shown in Fig. 11.

Alongside that, the typical connections such as the P, T, and Q connections are being researched. This is the typical steel bolted connections for bamboo construction as adapted from the Colombian code NSR 10.

(**a**) (**b**)

Fig. 11. Sample testing of foundation connection: (a) failure mode of embedded rebar; (b) tensile test for steel plate connections.

The guidelines described by ISO 12122-1:2014 ~ determination of characteristic values for timber structures are used to establish the characteristic values of the strength that will be determined by each test method. The sample size for each varies, to have an overview of the estimated strength, initial tests of smaller quantities can be done. The minimum quantity to provide adequate information for the characteristic value is 30 pieces. Although there is no established testing protocol for Bamboo connections, this test followed the guidelines described by ISO 22157:2019 on the test duration of the mechanical properties of bamboo. The guideline suggests having the connection fail within three to seven minutes. Linear Variable Differential transformers (LVDTs) are placed to measure the displacement that occurred within the specimens while testing.

1.2.4. Testing for walls and assemblages

For the utilization of bamboo as the main structural component of a composite shear wall, the BIC showcases its first-rate reaction frame capable of replicating lateral loads to full-size panels. Testing large assemblages, this reaction frame can produce monotonic and dynamic tests to evaluate the in-plane shear capacity of the composite bamboo shear walls. With a capacity of 100 kN in tension and compression, the use of the dynamic actuator can perform not only tests on the shear walls as per ISO 21581 but also tests on large-scale connections on actual construction components. To understand the behavior of the panels, the tested panels are being inspected for failure modes as shown in Fig. 12. Initial testing on panels includes Method II described in ISO 21581, where the rotation of the panels is permitted to assess the connections of the panels to the top and bottom supports.

Fig. 12. Reaction frame with the dynamic actuator (BIC).

1.3. Other research initiatives

As the capacity of BIC for research and development strengthens each year, internationally renowned institutions are also partnering with BASE. One of the major topics that the collaboration showcases is the integration of Life Cycle Assessment (LCA) in evaluating the lowering of the overall carbon footprint of CBFT construction when compared to traditional housing construction (Escamilla et al. 2022) as shown in Fig. 13. A recent study by Bundi et al. (2024) presented a dynamic LCA of bamboo housing which shows about a 70% reduction in total emissions compared to concrete brick buildings. With proper management of the bamboo plantation, these findings can be maximized and still be increased.

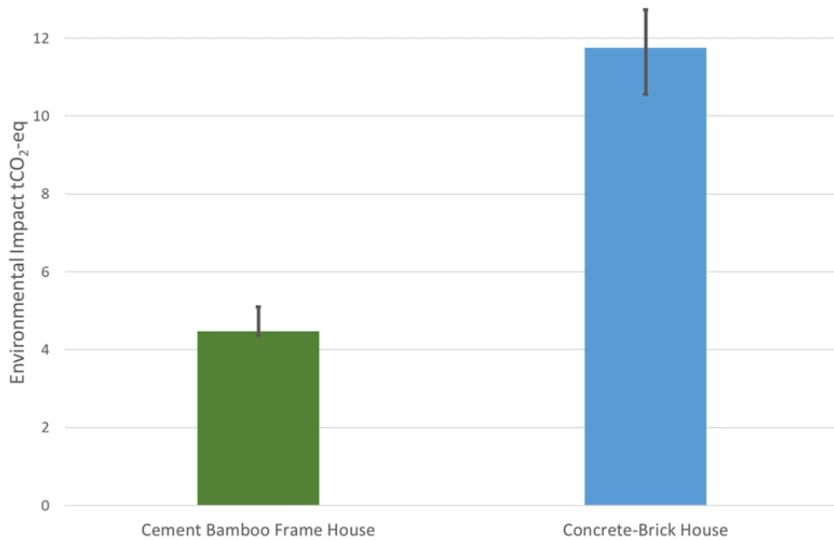
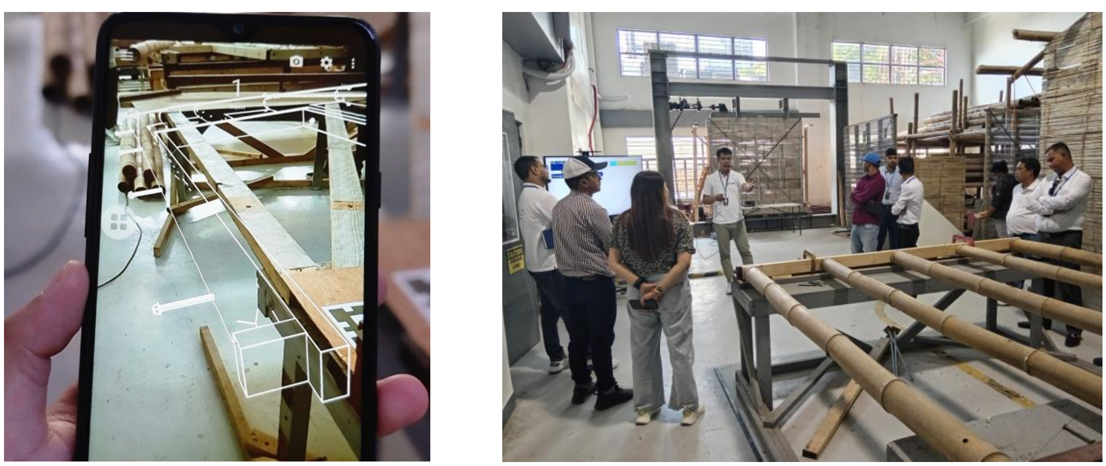


Fig. 13. Comparative Life Cycle Assessment between cement-bamboo frame house and conventional concrete-brick house (Escamilla et al. 2022).

The productivity of CBFT construction also matters in effectiveness as an alternative construction methodology. BASE is partnering with different research institutions to optimize the prefabrication process of CBFT. The application of augmented reality (AR) in the prefabrication of CBFT walls is being explored with Incon.ai, as shown in Fig. 14, which uses machine vision and artificial intelligence (AI) to enhance the productivity rate of construction. There are joint efforts also with Hilti, in designing equipment and types of machinery that can help ease lots of pain points in CBFT construction especially those that are still using manual efforts, such as injecting mortar infill inside the bamboo and fixation of bamboo studs to the dowels.



(a) **(b)**

Fig. 14. Optimization of CBFT prefabrication process with (a) augmented reality (AR) by Incon.ai, and (b) proper training of prefabrication.

Prefabrication of CBFT requires a certain skill set just like the construction of masonry and timber structures. Proper knowledge transfer on the correct procedures of prefabrication will improve the productivity rate. BASE is offering Continuing Professional Development (CPD) Programs to professionals under its Bamboo Academy. This showcases the correct procedures for handling bamboo, from its value chain, prefabrication process and up to the installation of the housing. Training programs are also being offered to partner organizations and contractors that are offering services in bamboo construction.

Conclusion

The ongoing and future research plan of BIC includes the completion of characteristic values for different bamboo species such as *Bambusa vulgaris* and *Dendrocalamus asper*. This will open the utilization of other bamboo species for the construction of socialized housing. The availability of bamboo species in specific areas may differ and affect the production of bamboo for structural use, thus, adding more characterized bamboo species to the list will help in the utilization of these untapped natural resources.

Continuous partnerships with the best research-oriented universities will help fill the gap in data gathering. For assemblages, characterization of full-scale tests will be done for walls with and without openings. Additional tests for the wall aspect ratio will also be included. The research plan includes the understanding of the mechanical properties and behavior of the material, following the investigation of the strength and behavior when applied to different connections, and verifying the performance through testing of assemblies and systems. With this trend that we see in research topics, the academe can assist not only in the gathering of data on the mechanical properties of certain bamboo species but also contribute to the development of new ideas and emerging topics in connections and assemblages.

Another area of developing research topics also includes the optimization of the production process and the modularity of the composite bamboo shear walls. Continuous improvement of the connections for the current design of CBFT will be made.

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