

INVESTIGATION OF THE SHEAR STRENGTH OF STEEL BOLTED BAMBUSA BLUMEANA T-CONNECTION

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ABSTRACT: Bamboo is a renewable resource, and its good mechanical properties support the idea that bamboo can be used in the construction industry as an alternative structural member. When a bamboo building is exposed to earthquakes and strong winds, it is important to ensure the reliability of its members and their connections. However, bamboo connections remain insufficiently studied. This study focuses on the shear strength of a T-connection using fish-mouthed bamboo secured with a J-bolt. The T-connection was tested with three variations of J-bolt diameter. In this study, 8 mm, 10 mm, and 12 mm were considered. In addition, the combination of being tested with mortar infill and clamp attachments was also considered. A T-test and regression analysis were used to determine the significance of these variables on the joint's shear strength. Results showed that the J-bolt size had no dominant effect since the bamboo failed first. However, the thickness and density of the bamboo were found to influence the connection's shear strength. Samples with both clamp attachments and mortar infill have higher strength than those without. The highest strength was the densest bamboo sample with clamp and mortar incorporated. Furthermore, connections without mortar behaved like roller support, while those with mortar acted as fixed support, offering greater flexibility in structural design. Case studies were conducted to assess the performance of T-connections in a 49 m² bamboo structure located near a fault line, considering both seismic and wind loads. Results showed that the connection is feasible for one-story, two-story, and three-story buildings.

Keywords: Bamboo, Shear Strength, T-connection, Clamp Attachment, Mortar Infill

1. INTRODUCTION

The UN-Habitat Philippines Country Report 2023 highlights a housing backlog of 6.5 million units [1]. To address this, *Bambusa Blumeana* is emerging as a sustainable structural material, particularly in low-rise buildings and indigenous structures due to its affordability, superior mechanical strength, and fast harvest rate of up to 4.87 culms/clump per year [2,3]. Despite its potential, adoption remains limited due to concerns about structural integrity, as typical bamboo connections are prone to shear failure and tensile failure. Assessment of bamboo tensile strength can usually be done following standard testing procedures, but the evaluation of shear strength, especially that of the bamboo connection, remains limited. The connections also lack uniform load distribution because bamboo's natural irregular shape makes it difficult to achieve connection uniformity [4].

Bamboo is a key component of the Cement Bamboo Frame Technology by Base Bahay [5]. Base Bahay Foundation, Inc. (BASE) is a non-profit organization based in the Philippines. It was initiated by the Hilti Foundation to provide alternative building technologies and enable a network of partners to build comfortable, affordable, disaster-resilient, and sustainable homes with social impact. This Cement Bamboo Frame Technology by Base Bahay utilizes reinforced concrete foundations, while beams and columns are made entirely of bamboo, connected with steel joints. This study focuses on T-

joints, in which one bamboo culm is connected perpendicularly to another. This connection enhances resistance to dynamic loads and lateral forces such as wind and seismic loads [6]. There are two bamboo parts in the connection. The tee is the vertical component of the connections and is one internode long. The stem is the horizontal portion and is two internodes long. This is shown in Fig. 1. This joint is termed the T-Joint Fish-mouth J-Bolt connection. The stem is intentionally made longer so that when the force is applied, the bulk of the reaction will act at the connection. To improve load distribution, fish mouths are carved at connection points, maximizing surface contact [7]. Although there are other ways of bamboo connections [8], this study explores J-bolts, which serve as a cost-effective alternative to steel or wood plates. This connection utilizes hooked rods to secure bamboo culms effectively, thereby enhancing the stability and reliability of the joints.

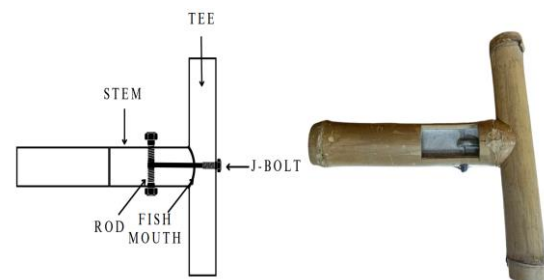


Fig.1 Steel bolted T-connection

The focus of this research is on the shear capacity of T connections in bamboo frames due to lateral loads. It should be noted that these bamboo structures are intended to be built in the Philippines, which is vulnerable to earthquakes and strong winds. The study is conducted to determine whether this type of connection is suited to housing projects in the Philippines. Specifically, this study will investigate how the geometric properties of bamboo, the dowel diameter, the presence of mortar, and the presence of clamps influence the shear capacity. Mortar infill is used to improve the strength of bamboo [9], especially at the connection. In particular, the study seeks to predict the shear capacity of T-Joint Fish-mouth J-Bolt connections under varying conditions using multilinear regression analysis. By doing this, insights into optimizing bamboo connections in construction may be achieved.

In summary, the goal of this research is to experimentally assess the shear strength of T-Joint Fish-mouth J-Bolt connections for bamboo frames. A simple model for the shear strength of the connection is also developed that can be used for earthquake analysis of bamboo frames.

2. RESEARCH SIGNIFICANCE

This study will help promote the adoption of bamboo engineering in the construction industry. The evaluation of the shear capacity of the connection is important to ensure the safety of bamboo structures, so that bamboo connections are better designed to accommodate the expected loads. Furthermore, the development of the connection can lead to innovative construction techniques that enhance the performance and aesthetics of bamboo structures. The research on the shear strength of the connection is not limited to house construction but can also be applied to other bamboo structures where shear stress in connections is critical.

3. METHODOLOGY

The experimental test was conducted in three phases. The first phase was to determine the strength of the mortar used to fill the connections. The second phase was the construction and testing of the connection. The last phase was to determine the properties of the bamboo used in the test, especially the moisture content and density.

3.1 Preparation of Bamboo For the T-Connection

The bamboo materials used in the construction of the bamboo joints were already chemically treated by Base Bahay to improve their durability. The bamboo was first cut into appropriate lengths, and its geometric properties were recorded. One end of the stem is then cut using a hole saw to produce a fish

mouth. The fish mouth will allow the tee and stem to connect smoothly. This ensures that a proper T-connection is formed. The stem is then inserted with a plain rod. The tee is then inserted with a J-bolt. Then, the J-bolt is tightened to hook the plain rod.

3.2 Preparation of J-bolt

The study utilized stainless steel rods in three distinct diameters: 8 mm, 10 mm, and 12 mm. These rods were then cut into 35- and 15-mm rods. The 35 mm rods were then bent and hammered into a J-bolt. The 15 mm rod is used as a lock for the J-bolt. The rod and the J-bolt are always of the same size.

3.3 Testing of Mortar

The mortar used in the study had a Portland cement-to-sand ratio of 1:3 and a water-to-cement ratio of 0.5. The mortar was then placed in 50 mm cube specimens and was subjected to a compressive test. Two batches were made, with 6 samples/batch. The average of each batch was determined to be the mortar strength. This is the mortar used as infill in the bamboo connection.

3.4 Testing of T-connection

A Universal Testing Machine (UTM) was used to determine the shear strength of the connection. The loading rate was set at 10 mm/min. A Linear Variable Differential Transformer (LVDT) was also used to measure the displacement of the connection as the load was applied. The bamboo tee was attached to a steel plate to keep it fixed as the vertical load is applied on the bamboo stem, as shown in Figure 2.

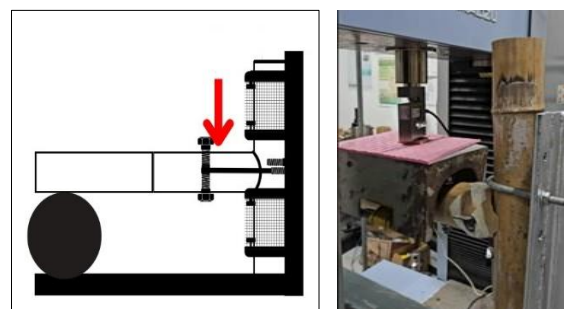


Fig.2 Loading setup (sketch on left, actual on right)

Four connection setups were considered in this study. This is aside from the variations due to the three different J-bolt sizes. The first setup was the connection with no mortar infill and with no clamp applied. The second setup still had no mortar infill but was applied with a clamp. The third setup had mortar infill but without a clamp. The fourth setup had both mortar infill and clamp.

To identify the test specimens associated with

these connection setups, Table 1 lists the label used for the test specimens in the experimental program. For example, 8CM-1 refers to an 8mm J-bolt, “C” for with clamp, “M” for with mortar, and 1 for the first trial out of 5. If “C” or “M” is not present in the label, this means that the clamp or the mortar is not present. Each setup was repeated five times, resulting in a total of 60 specimens.

Table 1. Labels for naming bamboo specimens

J-Bolt Size (mm)	Presence of Clamps	Presence of Mortar Infill
8, 10 & 12	C = Present Blank=Absent	M = Present Blank=Absent

3.5 Testing of Moisture Content and Density

After testing the specimens to evaluate the shear capacity, each specimen was deconstructed, and a piece of bamboo was cut into a rectangular prism. The piece was measured for its length, width, height, and weight. The sample was oven-dried for 24 hours. After drying, the sample was weighed again to measure the moisture content and the density of the bamboo. The moisture content and density of bamboo were expected to affect the strength of the bamboo and thus affect the strength of the connections.

4. RESULTS AND DISCUSSION

Two batches of mortar were prepared due to the numerous bamboo connection specimens prepared. The first batch of mortar had an average strength of 9.025 MPa, while the second batch had an average strength of 9.684 MPa. Through statistical analysis, it was determined that the values of the two batches were not significantly different.

4.1 Initial Findings

The initial findings based on the test results are presented here. The strengths obtained from the tests and the representative load displacement curve for each connection setup served as the basis in establishing the initial findings of the tests.

4.1.1 Without Mortar and Without Clamp Case

The average strengths for each J-bolt size for the specimens without mortar and without a clamp are shown in Table 2. Although the result shows a slight increase in strength as the bolt size increases, it will be shown later in the statistical analysis that the strength difference with respect to the size of the bolts was not significant.

Table 2. Average Strength for Specimens Without Mortar and Without Clamp

Bolt Size (mm)	Strength (kN)
8	2.51
10	2.95
12	3.02

Figure 3 illustrates two distinct peaks in the load-displacement curve as the loading progresses towards total failure. This is the case with no mortar and no clamp. Figure 3 is a representative curve for all specimens where mortar infill and clamps are absent, as they exhibited the same trend. The first peak represents the initial splitting of the bamboo, occurring at the fish's mouth region. This split is caused by the moment generated by the shear force applied by the UTM. The first peak failure was observed to be the same in all setups. The second peak varies depending on the setup. For configurations without a clamp and mortar, it results from the crack propagation beyond the internode.

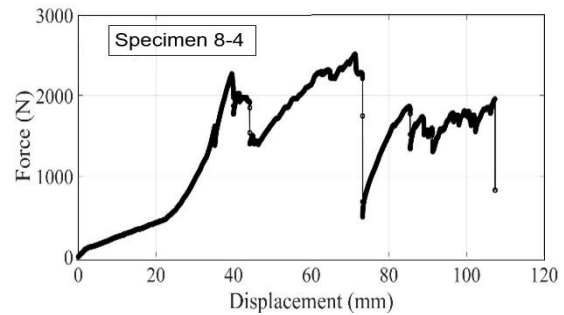


Fig.3 Load-displacement curve of 8 mm J-bolt connections (without mortar and without clamp)

4.1.2 Without Mortar and With Clamp Case

Table 3 presents the average strength recorded for each bolt size in this case of no mortar infill, but with a clamp. The presence of the clamp increased the measured strength of the connection.

Table 3. Average Strength Without Mortar and With Clamp

Bolt Size (mm)	Strength (kN)
8	4.92
10	5.72
12	5.63

Figure 4 represents all specimens in the case with clamps but without mortar infill. Again, the first peak represents the initial splitting of the bamboo, occurring at the fish's mouth region. The second peak for this case is attributed to the clamp's strength. The

failure of the clamp leads to a significant crack in the bamboo.

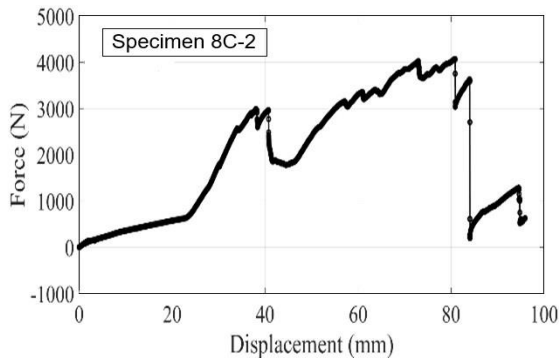


Fig.4 Load-displacement curve of 8C connections (with clamp but without mortar infill)

4.1.3 With Mortar and Without Clamp Case

The average strength of each bolt size for the case with mortar infill and without a clamp is tabulated in Table 4. For the 8 mm J-bolt, splitting of the steel rod was observed, which was not present in the larger diameter rods.

Table 4. Average Strength With Mortar and Without Clamp

Bolt Size (mm)	Strength (kN)
8	5.25
10	7.53
12	5.47

Figure 5 represents the case of specimens with mortar infill, but without a clamp. For this case, the second peak is related to the mortar's strength, with the connection weakening as cracks form in the mortar. The third peak is associated with the excessive cracks of bamboo without mortar. In configurations with mortar, this peak is linked to the strength at the internode. Once the crack extends through the internode, the strength diminishes. The final peak corresponds to the J-bolt, representing the highest strength achieved before complete failure.

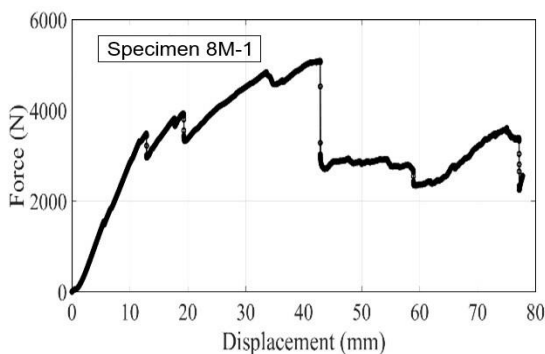


Fig.5 Load-displacement curve of 8M connections

4.1.4 With Mortar and With Clamp Case

Table 5 shows the average strength achieved by each bolt size for the case of with mortar and with a clamp. This connection setup resulted in the highest strength obtained from the test.

Table 5. Average Strength With Mortar and With Clamp

Bolt Size (mm)	Strength (kN)
8	13.58
10	12.49
12	17.37

Figure 6 represents the case with mortar infill and a clamp. It can be seen in the figure that only two peaks were observed before total failure. The first peak corresponds to the initial bamboo split, while the second peak represents the combined strength at the second internode, clamp, and mortar, which all fail simultaneously.

The measured connection strength differs significantly based on the connection configuration. In the setup without a clamp and mortar, the first peak is regarded as the connection's maximum strength, as the initial crack is enough to signify failure. In the setup with a clamp but without mortar, the second peak is considered the maximum strength. The first peak produces only a minor crack due to the clamp's ability to prevent further splitting. However, once the clamp fails, significant damage follows. For the setup with mortar but without a clamp, the third peak is identified as the connection's strength, as considerable damage occurs at that stage. Finally, in the configuration with both mortar and a clamp, the second peak is regarded as the connection's maximum strength since the damage at this instance is significant.

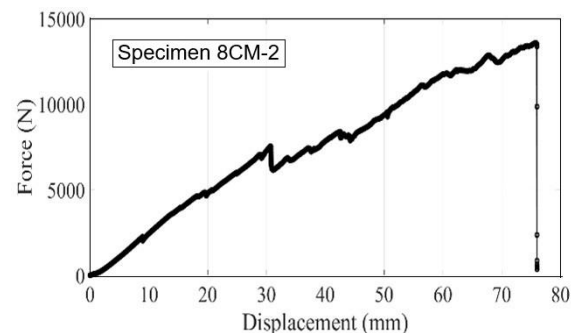


Fig. 6 Load-displacement curve of 8CM connections

4.2 Different J-bolt Sizes

It was found in Figure 7 that the sizes of the J-bolts did not make a significant difference in the shear capacity of the connection. A T-test with a 95% confidence level was also used to determine whether

there was a significant difference in the strength of the connection. It was found that even when all the connections had mortar infill or clamps the size of the bolt did not significantly affect the strength. If the variable that was changed was the J-bolt size, the shear capacity of the connection had no significant difference. This is because the bamboo fails first before the J-bolt.

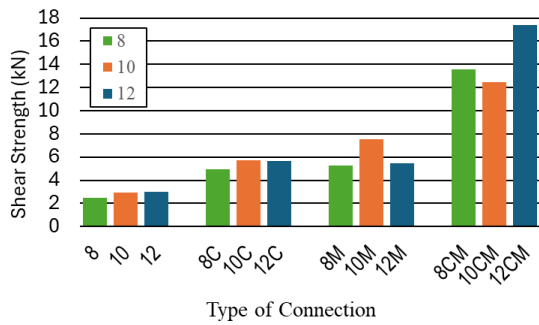


Fig.7 Comparison of Average Strength for Different J-bolt Sizes

4.3 Presence of Mortar Infill

Figure 8 indicates that connections with mortar infill exhibited significantly higher maximum strengths compared to those without mortar infill. A T-test with a 95% confidence level showed that the p-value of the with mortar infill versus without mortar infill was less than 0.05%. Furthermore, the connection without the mortar had a higher amount of displacement before the first peak of strength occurred. On the other hand, the setup with mortar infill displaced only by a minimal amount before the first peak occurred. It can be said here that the setup without mortar infill can be considered to have slide since it is able to move a significant displacement, while the setup with mortar infill can be considered as a fixed support since it can withstand the load with minimal displacement.

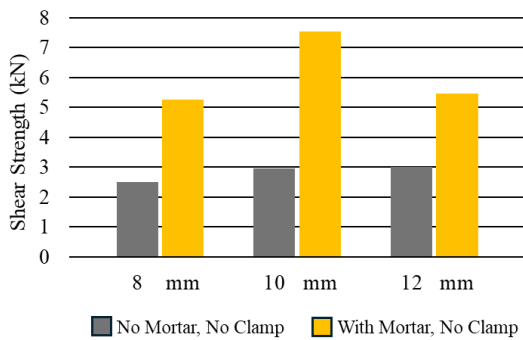


Fig.8 Comparison of Average Strength with Mortar and Without Mortar

4.4 Presence of Clamps

Figure 9 demonstrates a significant difference in connection strength between setups with and without clamps, with the clamped configuration exhibiting higher strength. A T-test with a 95% confidence level showed that the p-value of the with clamp versus without clamp was less than 0.05%. This proves that the clamp increases the shear strength of the connection. In terms of displacement, there is no significant difference between the with and without clamp setups.

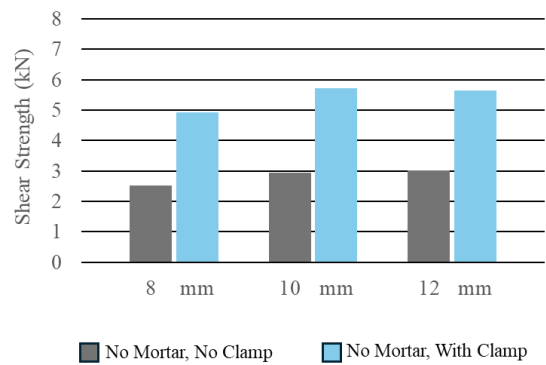


Fig. 9 Comparison of Average Strength with Clamp and Without Clamp

4.5 Presence of Mortar Infill and Clamps

Figure 10 shows that the setup with clamp and mortar had a higher strength than both the setup with only mortar infill and only clamp. A t-test conducted at a 95% confidence level revealed that the p-value for the comparison between the with clamp and with mortar setup, the with clamp setup, and the with mortar setup was less than 0.05, indicating a significant difference. This suggests that the setup with a clamp and with mortar is the best setup in terms of shear strength of the connection.

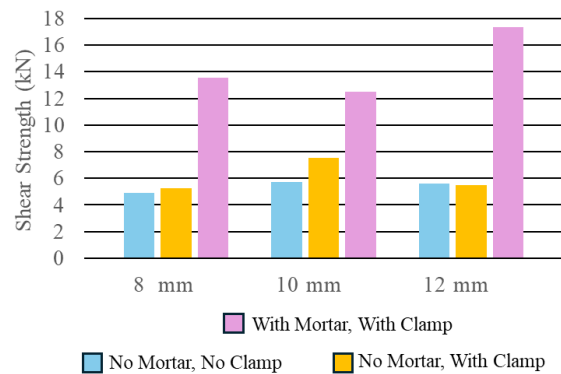


Fig. 10 Comparison of Average Strength with Mortar and with Clamp

4.6 Regression Analysis

A multilinear regression analysis was performed to determine the significant factors that contributed to the strength of the connection. The properties of the bamboo, mortar, clamp, and the size of the J-bolt were all included in the study. The regression analysis was iterated twice, since in the first iteration, there were factors that had a p-value higher than 0.05, which means they are not significant to the strength of the connection. In the second iteration, all factors exhibited a p-value of less than 0.05, indicating that each variable significantly influences the strength of the connection. These variables include stem thickness, stem bamboo density, mortar presence, and clamp presence. The regression also has an R-squared value of 0.798523, which means that 79.85% of the strength of the connection is contributed by the factors mentioned above. These findings further demonstrate that the presence of mortar and clamps effectively enhances shear strength. Moreover, the regression analysis indicates that the size of the J-bolt has a minimal impact on joint strength, with the geometric properties of the bamboo playing a more significant role.

4.7 Modelling

Based on the test results, two primary components govern the shear strength of the connection: the shear strength of the bamboo and the shear strength of the J-bolt. The bamboo's contribution concentrates in the upper portion of the stem, which directly resists the applied shear force. This region is most susceptible to splitting and shear failure. The performance of the connection depends on the interaction between these two components, with the bamboo resisting local bearing and shear forces. At the same time, the J-bolt provides the dowel action that transfers the load across the joint. Considering these observations, a simplified shear strength of the connection can be written as follows:

$$V_t = V_b + \alpha V_s \text{ kN} \quad (1) \quad (\text{in kN})$$

where $V_b = 0.016 (\gamma_b)(A_b)$

$$V_s = 0.6 (F_t)(A_s)$$

V_b is the shear strength of the bamboo, where γ_b is the bamboo density, and A_b is the cross-sectional area of the bamboo stem. The formula is based on the work of Bautista et al [10]. V_s is the shear strength of the steel J-bolt, where F_t is the tensile strength of the steel J-bolt and A_s is the cross-sectional area of the J-bolt.

Using the data from the experiment, V_b can be calculated based on the density and cross-sectional area of the bamboo stem. It should be noted that the density is affected by the moisture content of the

bamboo. The value of α can be determined through curve fitting, with $V_t - V_b$ being the dependent and V_s being the independent variable. This method minimizes the sum of squared differences to determine the value of α . The result of this process is presented in Table 6 for the different types of connections. Each connection setup was evaluated for the appropriate value of α .

Table 6. Connection Shear Strength Equations

Type of Connection	Proposed Shear Strength Equation (in kN)
No Mortar, No Clamp	$V_t = V_b + 0.0432 V_s$
No Mortar, With Clamp	$V_t = V_b + 0.0849 V_s$
With Mortar, No Clamp	$V_t = V_b + 0.1256 V_s$
With Mortar, With Clamp	$V_t = V_b + 0.4015 V_s$

As shown in Table 6, the connection with neither mortar nor clamp exhibited the lowest slope, that is, the lowest value of α . This indicates minimal utilization of the J-bolt's shear capacity. In comparison, the condition with mortar but without a clamp showed a steeper slope (larger value of α) than the configuration with a clamp but no mortar. The result suggests that mortar contributes more significantly to the utilization of the bolt's strength than clamp confinement alone. The condition combining both mortar and clamp achieved the steepest slope, resulting in the highest shear strength (largest value of α) among all connection setups. The equation in Table 6 demonstrates that the combined presence of mortar and clamp most effectively enhances the connection's load-carrying capacity.

Figure 11 is a comparison between the experimental and predicted shear strengths. Most of the data points lie above the reference line generated by the model, indicating that the predicted shear strengths are generally lower than the experimentally obtained values.

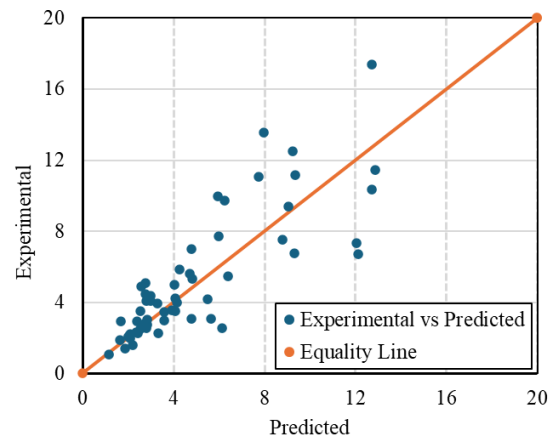


Fig. 11 Experimental vs Predicted Shear Strength

This conservative behavior suggests that the model provides safe estimates for most cases. However, some instances show values that fall on or below the reference line, implying that in these specific cases, the model underestimates the actual capacity, which may pose a safety concern if not adequately accounted for. These outliers underscore the importance of carefully considering the model's limitations in specific configurations. To ensure safe design, the usual strength reduction factor of 0.75 for shear is applied. The result is shown in Figure 12, which now shows a conservative prediction of strength.

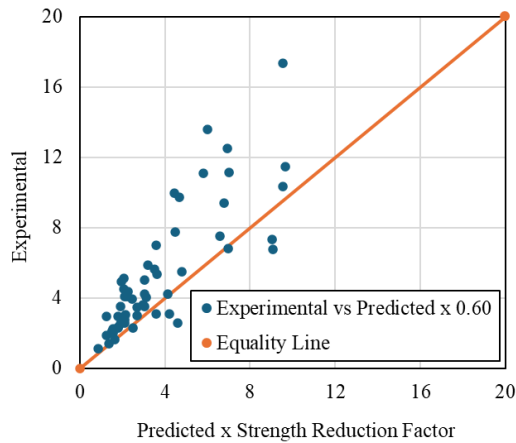


Fig. 12 Experimental vs Predicted Shear Strength Applied with Strength Reduction Factor

4.8 Case Study

A case study was conducted to determine the shear force a building in the Philippines will experience. Lateral forces acting on the building are assessed to determine whether the connection can withstand such forces. Three cases will be examined in this study: the first case is a one-story structure, the second case focuses on a two-story structure, and the third case considers a three-story structure. It will be assumed that there are only earthquake and wind forces that could affect the shear strength of the connection. Furthermore, the floor area is assumed to be 49 m², as data from the Philippines Statistics Authority (PSA) indicates that most housing units occupy this size. Lastly, it is assumed that the building is situated along a fault line, located in Zone 4, the highest seismic risk zone in the Philippines, and positioned in the windiest area of the Philippines, with the soil condition classified as soft soil and wind speed of 340 kph. The maximum earthquake and wind forces that the following buildings can experience are shown in Table 7. The values in Table 7 were calculated using the National Structural Code of the Philippines (NSCP).

Table 7. Maximum Earthquake and Wind Load

Building Type	Earthquake Load (kN)	Wind Load (kN)
3 Story	3.89	3.17
2 Story	2.93	2.12
1 Story	1.94	0.70

In all considered scenarios, seismic loading governs the structural design over wind loading. The regression analysis formula was used to estimate the shear strength of the connection, assuming the average of the thickness and density of the bamboo available is comparable to that used in the sample bamboo members. The values of the predicted shear strength can be observed in Table 8. The strength is adequate for earthquake load and wind load when compared to Table 7, specifically when mortar and clamp are used.

Table 8. Maximum Shear Strength Per Condition

Condition of Connection	Predicted Shear Strength (kN)	With Strength Reduction Factor (kN)
With Mortar and With Clamp	8.99	6.74
With Mortar and No Clamp	5.57	4.18
No Mortar and With Clamp	4.46	3.35
No Mortar and No Clamp	1.03	0.77

To ensure the structural integrity of connections of the building, elements of high density and substantial thickness must be employed, secured with clamps, and filled with mortar. It is possible for the connection to be used in one-story, two-story, and three-story structures. Furthermore, setting up with clamps and without mortar is sufficient to withstand the force experienced in all three structures. However, it should be noted that connections without mortar exhibit significant displacement. Therefore, using a mortar infill is still recommended for improved stability and performance.

5. CONCLUSION

It is concluded that the T-Joint Fish-mouth J-Bolt connection can be safely used for housing projects in the Philippines, where most residential structures are single-story but can extend up to 3-storey. This is supported by the finding that the connection can withstand shear forces for up to three-story buildings. The strength of the connection is reliant on the geometric properties of the bamboo. The selection of bamboo (with high density and substantial thickness)

is crucial to ensure the house's structural integrity. It is highly recommended to use mortar infill and a clamp. The presence of mortar and clamps also greatly improved the strength of the bamboo connection. It was found that the steel rod size does not significantly affect the strength of the joint, as shown in the test results. The utilization of T-connections presents a practical advantage for industry applications. Connections without mortar exhibited behavior akin to roller supports, whereas mortar-filled connections approximated fixed supports, thereby providing enhanced flexibility in structural design considerations.

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