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Short Report

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Parametric Analysis of a Numerical Model for *Guadua angustifolia*

Frames using finite element method

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Abstract

Guadua angustifolia has established as a sustainable material with high potential for low-rise rural constructions, especially in seismic regions. This study investigates the structural behaviour of bamboo frames under lateral loads, aiming to provide technical criteria for the design of rural housing. A total of 18 numerical models were developed in ANSYS APDL, combining two types of connections, three roof inclination angles (20°, 25°, 30°), and three aspect ratios ($L/H = 1.4, 1.5, 1.6$). PIPE288 elements were used for the bamboo, and COMBIN14 elements for the connectors. Mechanical properties were obtained from another research. The applied lateral loads ranged from 5 to 20 kN in increments of 5 kN. The model with an aspect ratio of 1.6 and a 30° inclined roof showed the highest lateral stiffness (0.2461 mm). Improved structural performance was observed with increasing inclination and slenderness of the frame. The results support the use of *Guadua angustifolia* as an efficient and sustainable construction solution for rural contexts, promoting the use of local materials and resilience to seismic events.

Keywords: *Guadua Angustifolia*, frames, numerical modelling, seismic behaviour, sustainable construction, parametric analysis.

Introduction

Currently, the construction sector is investigating sustainable materials that offer optimal mechanical properties. In this context, *Guadua angustifolia* has gained relevance due to its strength, lightness and flexibility, making it a viable alternative to traditional materials such as concrete and steel. Its rapid growth and abundance in countries such as Colombia, Japan and China reinforce its potential as a sustainable structural material [1]. Internationally, as part of the structural bamboo group, *Guadua angustifolia* and bamboo has attracted interest in regions of Asia, Africa and Latin America, where its use is being promoted in green building, social housing and climate change adaptation initiatives. Likewise, organizations such as ISO have begun to establish technical standards for its use in construction, recognizing its value within a global approach to sustainability. In addition, recent research has shown that bolt and mortar connections improve the load-bearing capacity of *Guadua Angustifolia* structures, allowing their application in more demanding structural systems [2]. These characteristics have prompted the development of studies aimed at better understanding its structural properties and its application in construction.

To effectively utilize the structural capabilities of *Guadua angustifolia*, a comprehensive assessment of its physical and mechanical properties is essential, drawing on established research. Previous studies have quantified its resistance to compression, bending, and tension, demonstrating its viability as a primary structural material for low-rise building construction [3]. However, challenges remain in the standardization of its design parameters, which limits its adoption compared to conventional materials. Recent studies have characterized the physical-mechanical properties of from different regions, optimizing its use in structural applications[3], [4], [5], [6], [7], [8], [9], [10]. However, it is important to consider that *Guadua angustifolia*, being a natural material, has a high variability in its properties due to factors such as the age of the stem, climate, soil type, and cutting and drying conditions. This heterogeneity can significantly affect the results of numerical models, so its incorporation and statistical analysis is key to obtaining more representative and robust simulations. These studies serve as sources of experimental data for implementation in numerical simulations.

This research proposes the modelling of structures with *Guadua Angustifolia*, making a parametric analysis. For this purpose, the Finite Element Method (FEM) will be used in linear

two-dimensional (2D) models, considering variations (1) in the aspect ratio (L/H), (2) the inclination of the roof and (3) the incorporation of new structural elements. These variations will allow the analysis of their impact on the stability and resistance of the structure, facilitating the optimization of the designs according to their constructive applications. The characterization of these frames will contribute to the generation of more efficient and functional models for their implementation in sustainable buildings.

The displacements, internal and external forces, and stiffness of the structural system have been analysed. In the FEM model, the structural elements of the *Guadua angustifolia* will be represented as components subjected to bending and compression, with properties assigned from the experimental research of authors [3], [4], [8], [9], [10]. The connection elements will be modelled as spring-damper type elements with uniaxial behaviour, whose stiffness values will be calculated based on the study data of this authors (Arbelaez & Correal, 2012; J., et al. Correal, 2011; Kou et al., 2022; Malkowska et al., 2022; Wang & Yang, 2020). From these results, it is expected to contribute to the development of modelling strategies that allow a more accurate representation of *Guadua Angustifolia*, facilitating its incorporation into seismically resistant structural designs.

FEM model used in the study

The analytical model of the portal frame with *Guadua Angustifolia* elements was based on the representation developed by Cely Ortiz (2023), who implemented a computational model to represent the behaviour of *Guadua Angustifolia* and bahareque walls under lateral loads.

The proposed model allows the calculation of the internal forces and deformations of the frames, considering the stiffness of the bamboo and the connections between the elements. The idealization of these components is shown in Figure 1.

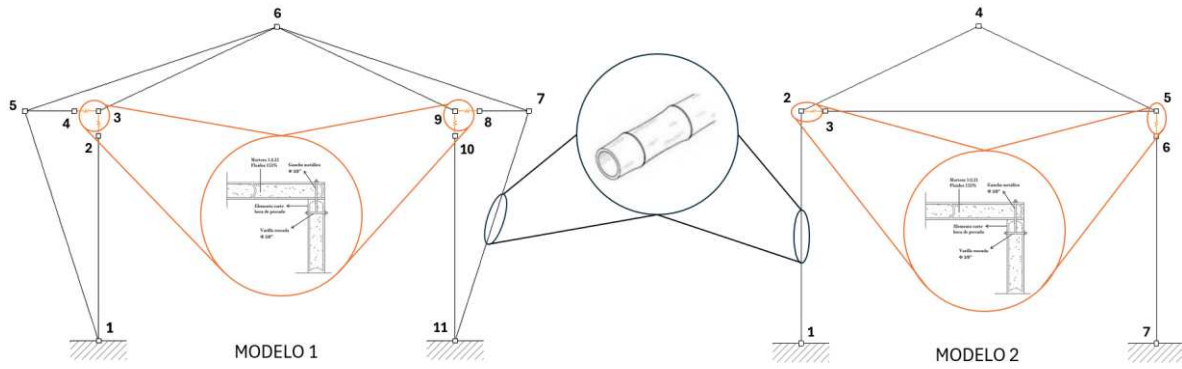


Figure 1. Idealization of the elements of the Guadua Angustifolia portal. Own elaboration.

The structural behaviour of the elements used is briefly described below:

1. Structural elements (beams and columns): These are modelled as elements subjected to bending and compression depending on their position. Each has 6 degrees of freedom (DOF) per node (three translational and three rotational), as shown in Figure 2(a). The stiffness matrix of these elements is well known because it is based on Timoshenko's first-order shear deformation theory.
2. Connecting elements: They were idealized by spring-damper type elements with uniaxial behaviour, each with three degrees of freedom (DOF) per node, as shown in Figure 2(b).

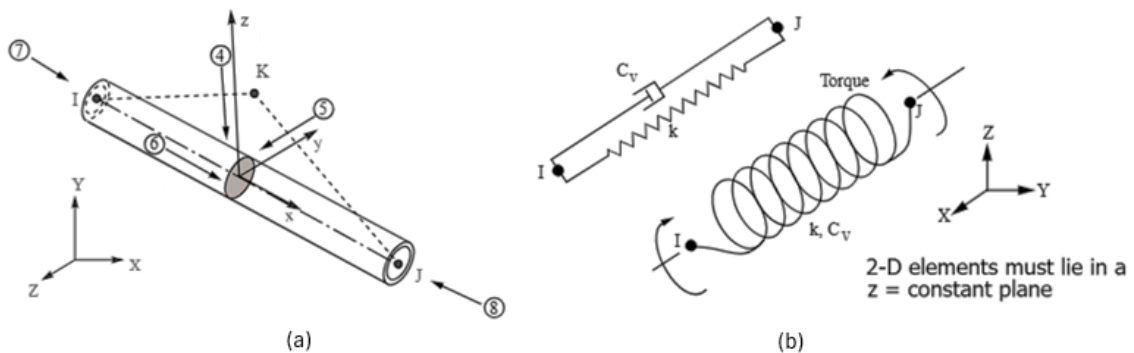


Figure 2. Element geometry of the FEM model: (a) structural element (PIPE288), and (b) connecting element (COMBIN14). Mechanical APDL Element Reference, 2011.

The stiffness matrix of the PIPE288 tubular element with six degrees of freedom per node is obtained by the following integral, based on the theory of Timoshenko & Gere (1961):

$$K = \int L[B]^T[D][B]dx \quad (1)$$

where L is the element length, [B] is the deformation matrix, and [D] is the constitutive matrix that includes bending, torsion, and shear effects. The matrix [B] is constructed from the shape functions N1 and N2, which describe the behaviour of the element as a function of its spatial coordinates. Its structure is:

$$B = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & 0 & 0 & 0 & 0 & \frac{\partial N_2}{\partial x} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{\partial N_1}{\partial y} & 0 & N_1 & 0 & 0 & 0 & \frac{\partial N_2}{\partial y} & 0 & N_2 & 0 & 0 \\ 0 & 0 & \frac{\partial N_1}{\partial z} & 0 & N_1 & 0 & 0 & 0 & \frac{\partial N_2}{\partial z} & 0 & N_2 & 0 \\ 0 & \frac{\partial N_1}{\partial z} & \frac{\partial N_1}{\partial y} & 0 & 0 & N_1 & 0 & \frac{\partial N_2}{\partial z} & \frac{\partial N_2}{\partial y} & 0 & 0 & N_2 \\ 0 & 0 & 0 & \frac{\partial N_1}{\partial x} & 0 & 0 & 0 & 0 & 0 & \frac{\partial N_2}{\partial x} & 0 & 0 \end{bmatrix} \quad (2)$$

This matrix relates the nodal displacements to the deformations, ensuring that the formulation of the problem is consistent with the structural theory used. On the other hand, the matrix [D] includes the mechanical properties of the material and of the pipe profile; this matrix reflects the response of the material to the internal forces, which is fundamental for the calculation of the stiffness of the element. Its structure is as follows:

$$[D] = \begin{bmatrix} E & 0 & 0 & 0 & 0 & 0 \\ 0 & EI_z & 0 & 0 & 0 & 0 \\ 0 & 0 & EI_y & 0 & 0 & 0 \\ 0 & 0 & 0 & GJ & 0 & 0 \\ 0 & 0 & 0 & 0 & K_s GA_s & 0 \\ 0 & 0 & 0 & 0 & 0 & K_s GA_s \end{bmatrix} \quad (3)$$

In this case, E represents the modulus of elasticity, G the shear modulus, I the moment of inertia in the Z and Y axes, and Ks the shear correction coefficient.

Geometric and mechanical characteristics of the portal frame elements

Two portal frame models were proposed with different dimensions. The Guadua elements have a span (L) of 4.4 m and heights (H) of 2.8, 3.0 and 3.2 m. Consequently, the aspect ratio (L/H) varied between 1.4 and 1.6.

The portal beams were modelled as orthotropic elements with a circular cross-section of 0.14 m outer diameter and 0.125 m inner diameter. The columns, on the other hand, have a circular cross-section with an outer diameter of 0.18 m and an inner diameter of 0.16 m. Based on these values, the ratio between the moment of inertia of the beam (I_b) and that of the column (I_c) is approximately 0.36, indicating that the bending stiffness of the column is significantly higher than that of the beam.

The flexural and compressive moduli of elasticity for *Guadua angustifolia* were determined through material characterization studies conducted in Villavicencio, Meta (Rincón, 2024). The Poisson's ratio values were derived from complementary research employing image processing techniques to analysed the internal structure of *Guadua angustifolia* (Osorio, Vélez & Ciro, 2007). With these values, the shear modulus (G) was calculated in both bending and compression, using the equation (4).

$$G = \frac{E}{2(1 + \nu)} \quad (4)$$

The finite element method has a wide range of applications for different types of connections, but for this research it was chosen to represent the fish mouth connection because, according to Correal (2011), it is the most efficient according to the creep theory (EYM). In the ANSYS modelling, this connection was represented by a spring-damper type element (COMBIN14).

The following real constants were assigned to this element: the stiffness (K), obtained from the stress-strain plot of the fish mouth joint according to Correal (2011), and the damping coefficient (c), calculated as $c = 2mW_n\zeta$. To estimate the mass (m), the combined weight of the guadua and concrete in a length of 0.45 m was considered, together with their respective cross section and a damping ratio (ζ) of 0.04.

The values assigned to the different elements of the finite element model (FEM) are as follows:

$\nu = 0.28$ (Poisson's Coefficient)

$E_x = 14482.52$ MPa (Modulus of elasticity in bending)

$E_y = 12958.62$ MPa (Modulus of elasticity in compression)

$G_x = 5657.23 \text{ MPa}$ (Modulus of shear in bending)

$G_y = 5061.96 \text{ MPa}$ (Modulus of shear in compression)

$K = 1114529.85 \text{ N/mm}$ (Stiffness)

$c = 318.59 \text{ Ns/mm}$ (Damping coefficient)

Parametric Study

This study evaluates the variations in the behaviour of Guadua Angustifolia portal frames by changing the following parameters:

1. Type of model (Inclusion of more structural elements).
2. Aspect ratio (L/H) (Variation of heights).
3. Roof inclination (Modification of the roof angle).

All cases were subjected to a lateral load of 20 kN, applied at the upper left corner of the portal frame. For each model analysed, the following results were compiled:

1. lateral displacements (Δ).
2. Stiffness of the portal frame (K).

Effect of aspect ratio and deck inclination on the lateral displacement of guadua frames

Numerical modelling of the frames was developed in ANSYS APDL, subjecting them to increasing lateral loads of 5, 10, 15 and 20 kN. During the simulation, three aspect ratios were considered ($L/H = 1.4, 1.5$ and 1.6), as well as three roof inclinations: $20^\circ, 25^\circ$ and 30° . The response parameter analysed was the total lateral displacement, expressed in millimetres (mm).

Lateral load-displacement behaviour Model 1. Table 1 presents the lateral displacements for different load stages in Model 1, with a deck inclined at 20° . Figure 4 (a) shows the corresponding load-displacement curves. It is observed that a lower aspect ratio produces

larger displacements. In particular, the model with aspect ratio 1.5 has a 20 % larger displacement than the one with aspect ratio 1.6.

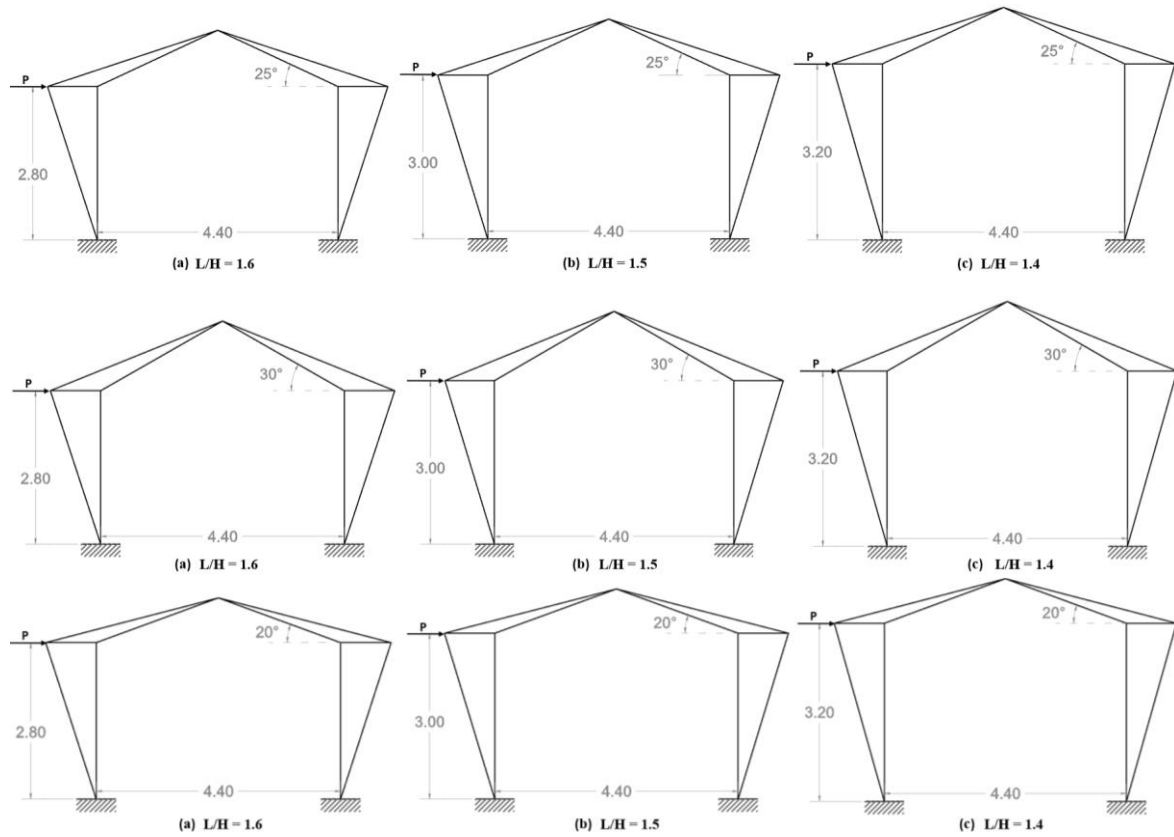


Figure 3. Frames of Model 1 with a 20°, 25° and 30° inclined roof and modelled according to their aspect ratio (a) $L/H = 1.6$, (b) $L/H = 1.5$, and (c) $L/H = 1.4$.

Table 1. Lateral displacement for different aspect ratios for Model 1 with a 20° Roof Inclination.

Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.109270	0.092193	0.076892
10	0.218540	0.184385	0.153785
15	0.327805	0.276575	0.230675
20	0.437075	0.368770	0.307570

Table 2 shows the lateral displacements recorded for Model 1 with 25° tilt. The results reflect an inverse relationship between aspect ratio and displacement magnitude. Figure 4 (b) shows that, as the L/H ratio decreases, the structural deformability increases. The model with ratio 1.4 presents a lateral displacement 18 % higher than the model with ratio 1.5, suggesting

lower energy dissipation capacity and lower structural stiffness. This behaviour could be related to the increased slenderness of the system, which makes it more vulnerable to deformation under lateral loads.

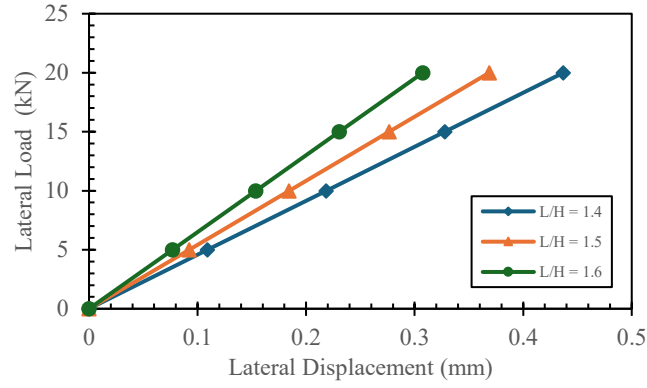
Table 2. Lateral displacement for different aspect ratios for Model 1 with a 25° Roof Inclination.

Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.096835	0.082033	0.068711
10	0.193675	0.164065	0.137420
15	0.290505	0.246100	0.206135
20	0.387345	0.328135	0.274845

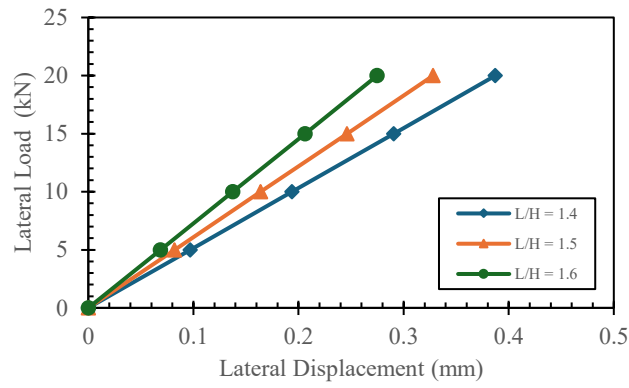
Table 3 details the lateral displacements for Model 1 with a 30° deck, while Figure 4 (c) illustrates their evolution against increasing loads. As in the previous cases, a lower aspect ratio is associated with higher displacements. Of note is the model with ratio 1.4, which achieves 40 % more displacement compared to the one with ratio 1.6, reaffirming the influence of geometry on structural performance against horizontal loads.

Table 3. Lateral displacement for different aspect ratios for Model 1 with a 30° Roof Inclination.

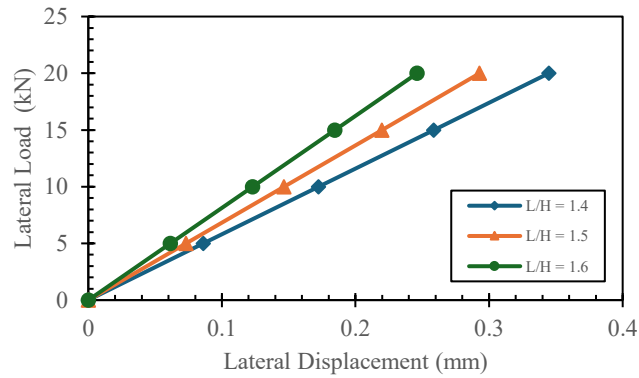
Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.086178	0.073233	0.061546
10	0.172355	0.146465	0.123090
15	0.258530	0.219695	0.184635
20	0.344710	0.292930	0.246185



(a)



(b)



(c)

Figure 4. Load-displacement curves for frames of Model 1 with a 20°, 25° and 30° inclined roof and different aspect ratios.

In general, for a constant lateral load, the frames with the lowest aspect ratio ($L/H = 1.4$) had the largest lateral displacements, reflecting lower structural stiffness. In contrast, those with

$L/H = 1.6$ showed better performance, with smaller displacements and greater stability. For example, under a load of 20 kN, the lateral displacement decreased from 0.437 mm (20° deck) to 0.344 mm (30° deck), highlighting the positive effect of a higher deck slope.

This behaviour can be explained by the triangulation induced by the slope, which favors load redistribution and improves the structural response to lateral actions. From a design approach, a higher roof slope can be applied as a passive strategy to improve seismic performance without significantly increasing costs.

The most efficient configuration was the 30° deck with $L/H = 1.6$, reaching a minimum displacement of 0.246 mm under 20 kN, equivalent to a structural efficiency of 0.0123 mm/kN. In contrast, the least favourable configuration (20° deck with $L/H = 1.4$) presented an efficiency of 0.0218 mm/kN, which reinforces the influence of these geometric variables on lateral stiffness.

Based on the results obtained in the first model, we proceed with the analysis of Model 2, maintaining the comparative approach and the methodology previously applied. This model presents an alternative geometric configuration with respect to the previous one, which allows a more accurate evaluation of the differences in the structural behaviour against lateral loads. As in the first case, three roof inclinations (20° , 25° and 30°) and three aspect ratios ($L/H = 1.4$, 1.5 and 1.6) were considered, under equivalent lateral load conditions, which facilitates a direct comparison between both models and allows identifying the impact of geometric variations on stiffness and lateral displacements.

Lateral load-displacement behaviour of Model 2. Table 4 and Figure 6 (a) present the lateral displacements for a 20° deck. It is again evident that the lower the aspect ratio, the larger the displacements. Ratio 1.5 showed an increase of 23% with respect to ratio 1.6, confirming the trend that slender structures are more vulnerable to horizontal actions.

As in the previous model, patterns of behaviour associated with both the variation of the aspect ratio and the slope of the roof are identified. However, there are relevant differences in the magnitude of the displacements, suggesting that the geometric configuration of this second model significantly influences its structural response.

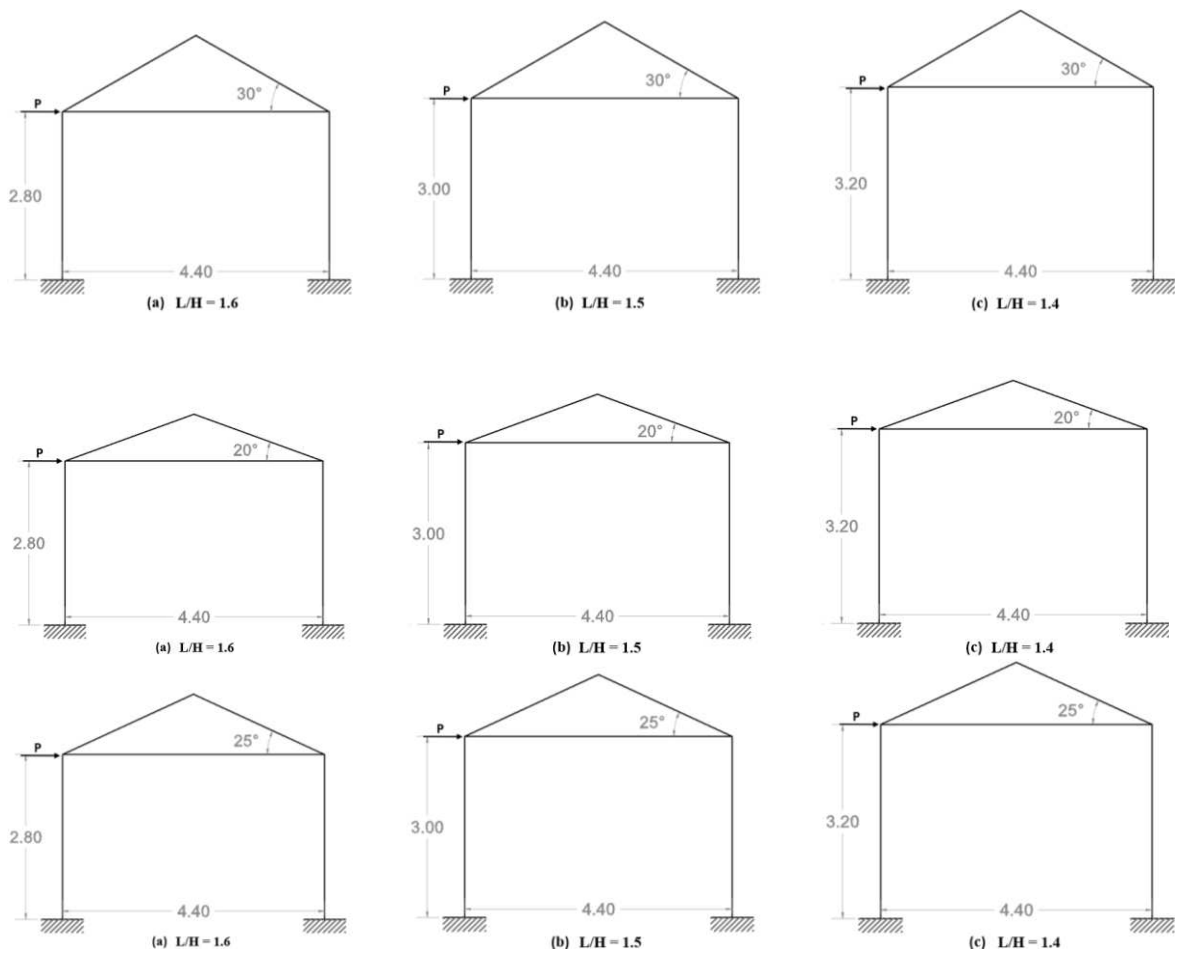


Figure 5. Frames of Model 2 with a 20°, 25° and 30° inclined roof and modelled according to their aspect ratio (a) $L/H = 1.6$, (b) $L/H = 1.5$, and (c) $L/H = 1.4$.

Table 4. Lateral displacement for different aspect ratios for Model 2 with a 20° Roof Inclination.

Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.294020	0.242890	0.198090
10	0.588040	0.485780	0.396190
15	0.882060	0.728660	0.594280
20	1.176100	0.971550	0.792380

Table 5 shows the lateral displacements of Model 2 with the deck inclined at 25°. The curves in Figure 6 (b) reflect an increase in deformability with decreasing L/H ratio. The model with

ratio 1.4 presented a 21% higher displacement than the model with ratio 1.5, indicating a higher slenderness and a lower energy dissipation capacity under lateral loads.

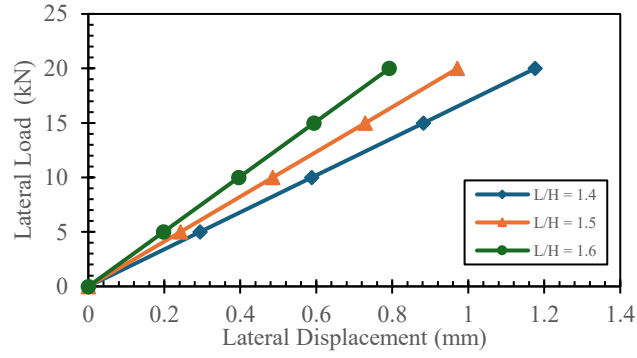
Table 5. Lateral displacement for different aspect ratios for Model 2 with a 25° Roof Inclination.

Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.294020	0.242890	0.198090
10	0.588040	0.485780	0.396190
15	0.882060	0.728660	0.594280
20	1.176100	0.971550	0.792380

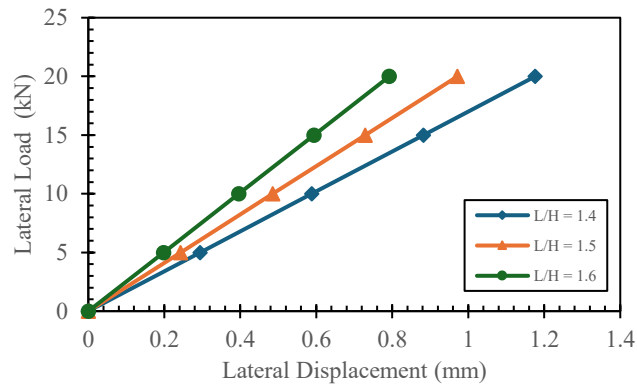
In the case of the 30° deck, Table 6 and Figure 6 (c) show the corresponding lateral displacements. The results follow the same trend: the lower the aspect ratio, the higher the deformability. The model with $L/H = 1.4$ had a 48% higher displacement than the 1.6 ratio model, confirming the significant impact of geometry on stiffness under horizontal loads.

Table 6. Lateral displacement for different aspect ratios for Model 2 with a 30° Roof Inclination.

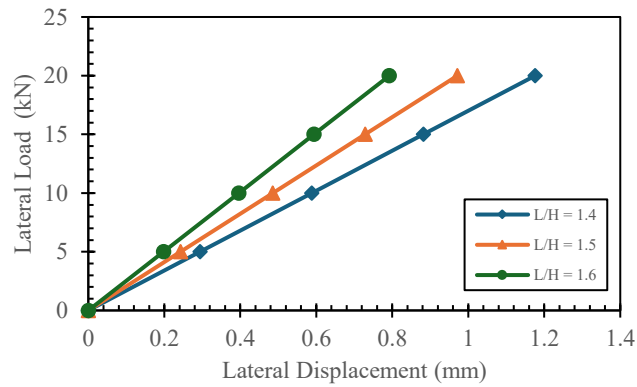
Lateral Load (kN)	Lateral Displacement (mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
5	0.294020	0.242890	0.198090
10	0.588040	0.485780	0.396190
15	0.882060	0.728660	0.594280
20	1.176100	0.971550	0.792380



(a)



(b)



(c)

Figure 6. Load-displacement curves for frames of Model 2 with a 20°, 25° and 30° inclined roof and different aspect ratios.

In the case of Model 2, it is observed that the results obtained for the different roof inclinations (20°, 25° and 30°) are identical, which, although it might initially appear to be an error, responds to a particular structural characteristic of this model: the presence of a rigid

horizontal element located at the node where the lateral load is applied. This configuration creates a local stiffness condition that significantly restricts the effect of the roof inclination on the overall response of the system, especially in terms of lateral displacement and stress distribution. As a result, the variation of the deck angle does not appreciably affect the structural behaviour, which justifies the similarity of the data presented in the tables.

One of the most relevant aspects is that, although in all cases a lower aspect ratio leads to greater displacements, the sensitivity of the structure to this variation is not uniform. As the inclination of the roof increases, the difference in behaviour between the different values of L/H becomes more pronounced. This phenomenon suggests that there is a non-linear interaction between the roof pitch and the slenderness of the portal frame, where certain angles can amplify or attenuate the negative effects of a slender geometry.

Likewise, it is observed that increasing the roof pitch tends to generate a slight improvement in performance against lateral loads, although this improvement alone is not sufficient to offset the negative effects of a low aspect ratio. In fact, in the case of $L/H = 1.4$, even with a 30° slope, displacements are still significantly higher compared to more compact configurations.

Another noteworthy observation is the consistency of the mechanical behaviour of the model in each of the loading stages. Despite the progressive change in the applied force levels, the evolution of the displacements maintains a logical and staggered progression, suggesting a stable structural response, without discontinuities or evident nonlinear behaviour within the load range evaluated.

Stiffness behaviour against lateral load Model 1. The results obtained and recorded in Table 7 and Figure 7 show that both the increase in the aspect ratio and the increase in the roof inclination generate a progressive improvement in the lateral stiffness of the portal frame. As the L/H ratio increases from 1.4 to 1.6, a steady growth in stiffness values is observed, regardless of the tilt angle. Similarly, the inclination of the roof contributes positively to the increase in stiffness at each of the analysed levels. The configuration that presented the best performance corresponds to an aspect ratio of 1.6 and a deck inclination of 30° , reaching a maximum stiffness of 81.24 kN/mm. This behaviour suggests that slender structures with

steeper roofs respond more efficiently to lateral loads, which is fundamental for seismic design in rural areas.

Comparing the least stiff case (L/H 1.4 and 20°) with the most efficient case (L/H 1.6 and 30°), the stiffness increases by 77.5%, from 45.76 kN/mm to 81.24 kN/mm. This demonstrates the significant impact of the geometric parameters on the structural performance of the Guadua portal frames.

Table 7. Stiffness of the Frame according to Aspect Ratio and Roof Inclination of Model 1.

Roof Inclination (°)	Frame Stiffness (kN/mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
20	45.76	54.23	65.03
25	51.63	60.95	72.77
30	58.02	68.28	81.24

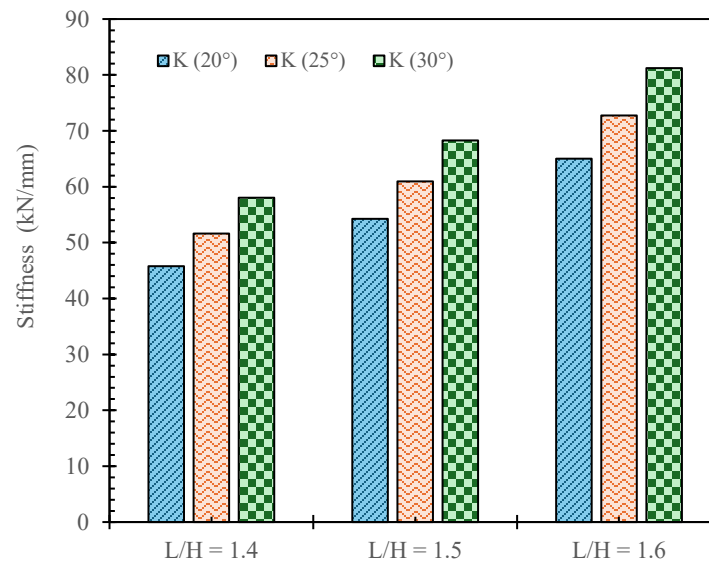


Figure 7. Behaviour of the Frame Stiffness in Model 1 under changes in Aspect Ratio and Roof Inclination.

Stiffness behaviour against lateral load Model 2. It is observed that the stiffness of the portal frame remains constant for each aspect ratio value, regardless of the variation of the roof inclination angle. As presented in Table 8, for an L/H ratio of 1.4 the stiffness remained at 17.01 kN/mm; for L/H = 1.5 it was 20.59 kN/mm, and for L/H = 1.6 it reached 25.24 kN/mm. This behaviour suggests that, in this structural configuration, the roof inclination does not significantly influence the stiffness of the system, unlike Model 1 where a clear sensitivity to this parameter was observed. This behaviour is clearly visualized in Figure 8, where the three curves corresponding to angles of 20°, 25° and 30° overlap, showing an independence between the roof inclination and the stiffness response of the system. The percentage increase in stiffness between aspect ratios is also consistent: going from L/H = 1.4 to L/H = 1.6 shows an increase of 48.4 %, confirming that horizontal geometry (L/H) remains a determining factor in structural stiffness, even when other parameters do not generate variations. This pattern suggests that Model 2 is less sensitive to changes in roof slope, which could be attributed to a different or less effective arrangement of diagonal elements or stiffeners in its configuration.

Table 8. Stiffness of the Frame according to Aspect Ratio and Roof Inclination of Model 2.

Roof Inclination (°)	Frame Stiffness (kN/mm)		
	Aspect ratio (L/H)		
	1.4	1.5	1.6
20	17.01	20.59	25.24
25	17.01	20.59	25.24
30	17.01	20.59	25.24

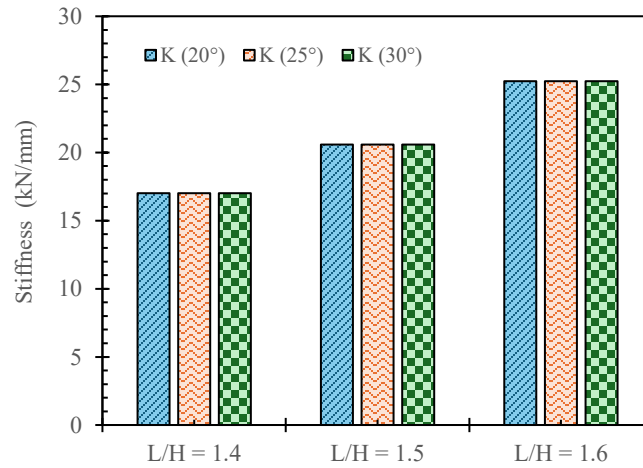


Figure 8. Behaviour of the Frame Stiffness in Model 2 under changes in Aspect Ratio and Roof Inclination.

Conclusions

The results presented in this study are based on experimental values of lateral displacement, as well as on the orthotropic properties obtained experimentally for the analysed frames. These data were integrated in a numerical modelling by means of the Finite Element Method (FEM) under a linear formulation, which allowed obtaining results with a higher degree of approximation to the real structural behaviour.

It was evidenced that Model 1 presents a more efficient structural performance compared to Model 2. This efficiency is attributed to the greater number of structural elements present in its configuration, which allows a better dissipation of the acting forces. Likewise, the inclusion of a greater number of diagonal elements in the structural system favors a more balanced redistribution of loads, improving the response to lateral actions and, consequently, optimizing its seismic behaviour.

The structural behaviour of the frames with connectors (COMBIN14) largely depends on their configuration. In systems with a limited number of structural elements, the inclusion of connectors can lead to an increase in overall flexibility, thereby reducing the lateral stiffness of the structure and promoting mechanisms of instability or premature structural failure. The implementation of connectors (COMBIN14) is limited to straight elements, as their

application in diagonal elements is not structurally viable. Furthermore, their use should be restricted to a single connector per element; placing connectors at both ends of the same element results in a significant increase in system flexibility, which may induce premature failure mechanisms.

In Model 1, it was observed that the increase in both aspect ratio and roof inclination contributed to a reduction in lateral displacement and an increase in the structural stiffness of the frame. However, in Model 2, although the increase in aspect ratio continued to show a positive effect in reducing lateral displacement, the variation in roof inclination did not produce significant changes in displacements or in lateral stiffness, which remained constant. The most efficient configuration was identified as Model 1 with an aspect ratio of 1.6 and a roof inclination of 30° , since under this condition the highest lateral stiffness recorded in the study was achieved, with a value of 0.2461 mm.

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