

# Behavioural Analysis and Internal Stress Evaluation of Glue-Laminated Bamboo Space Truss Utilising Carbon Fibre-Reinforced Composite Joints

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## Abstract

Truss is a structure composed of straight members forming triangular panels. Truss typically assumes a rigid configuration with connections treated as flexible joints. A commonly used material for truss construction is A36 steel, but due to its lack of sustainability, engineers and architects are increasingly exploring alternatives. Traditionally employed in construction, bamboo has gained attention for its impressive mechanical properties, positioning it as a viable substitute for steel. This research emphasises the utilisation of Glulam, a glue-laminated bamboo, as a component in space trusses. The modular tetrahedral space truss is constructed using six Glulam members connected by carbon fibre-reinforced composite joints. The primary objective of this study is to assess the truss prototype's behaviour under various loading magnitudes through practical experimentation. The researcher treated bamboo culms with a boric salt solution, stripped them, and glued them together to form the truss member. Space truss joints were created using a 3D printer. The prototype underwent axial loading ranging from 0 to 490 N at its apex. Stresses, strains, and deformations were measured using LiDARs and strain gauges in an instrumentation setup. The findings suggest that the connectors exhibit elasticity before the Glulam reaches its proportional limit stress of 59 MPa. Experimentation produced nodal displacement-load curves displaying significant linearity, indicating elastic behaviour in connectors and members, where stress corresponds to strain. This underscores the promising potential of Glulam and fibre-reinforced composites as materials for truss components.

## 1. Introduction

Framed structures are commonly employed in the construction sector for erecting buildings, towers, bridges, and diverse architectural edifices. These structures are the fundamental framework or skeleton, which ensures structural robustness. An example of this structure is the truss, a configuration of interconnected straight elements linked by flexible joints. These elements combine to form triangular panels, culminating in a sturdy and unyielding arrangement [1]. The replication of such truss-like designs observed in natural formations underscores

the aspiration to diminish stress while optimising strength, leveraging the load-bearing capacity of each truss component [2].

In truss construction, steel stands out as a prevalent material choice. Typically, structural steel is fashioned from plain carbon steel, denoted as ASTM 36 or A36. This material boasts a yield stress of 249 MPa and a tensile strength ranging between 400 MPa and 550 MPa. The appeal of this specific steel variant lies in its ability to undergo substantial deformation before fracture, a property commonly termed ductility [3]. However, the extensive use of steel in construction has raised environmental concerns stemming from the adverse repercussions of steel mining. Being a resource-intensive material, steel is burdened with weightiness and significant carbon emissions during its manufacturing process. To counteract these challenges, timber has emerged as a sought-after alternative for crafting trusses. In the Philippines, timber varieties are categorised based on their strength characteristics, spanning from moderately low-strength species like Almaciga wood with a tensile strength parallel to the grain measuring 7.35 MPa to high-strength species like Yakal wood with a tensile strength parallel to the grain measuring 15.30 MPa [4], [5]. Due to its rapid growth rate and natural abundance, bamboo has garnered recognition as an exceptionally sustainable material. It has found diverse applications in construction, with its physical attributes rendering it a promising and cost-effective substitute for steel [5]. For instance, its tensile strength rivals that of steel, rendering it suitable for numerous structural applications.

Various studies have cited the potential of bamboo as a truss material. The performance of bamboo culms when used in space and plane trusses has been evaluated and shows promising results due to bamboo's high tensile strength-to-weight ratio [6]. Mechanical properties of bamboo used in these studies found that bamboo can exhibit a tensile strength ranging from 136 MPa to 340 MPa and a modulus of elasticity from 10,000 MPa to 20,000 MPa. [7]-[11]. The strength of bamboo varies among species and regions, but other factors like the selection of culm and treatment methodologies affect these values. Researchers have identified ways to select culms of bamboo suitable for utilisation in making trusses [8], [12].

Glue-laminated bamboo (Glulam) is another option for engineers to utilise bamboo as structural members. It is an assembly of glued strips of bamboo forming a timber-like structure. Most of the studies used *Yushiana alpina*, a bamboo species, and have described that Glulam truss members using this species can exhibit a tensile strength of up to 360 MPa. It was also cited that the Glulam material tested meets the structural requirements according to conventional wood specifications and can be used as a construction material [12], [13].

The plentiful and renewable nature of bamboo presents an attractive and sustainable avenue for mitigating the ecological footprint of construction activities, all while providing economic advantages [14]-[16]. This paper presents the behavioural analysis and stress evaluation of a space truss with glue-laminated bamboo members made from *Bambusa blumeana* strips and joints made from carbon fibre-reinforced composite.

## 2. Materials and Methods

The sequence of the research's progression is depicted in Fig. 1. The methodology was formulated with the intention of accomplishing the research objectives. The selection of materials, determination of mechanical properties of Glulam, and evaluation of theoretical behaviour of Glulam space truss were taken based on an investigation conducted by Lucena et al. [17]. The methodology on nodal behaviour and internal stress analysis was performed using laboratory experimentation with the aid of different sensors. The results from the experimentation will be compared to the theoretical results.

This paper presents the experimentation methodology on the actual behaviour of a truss prototype composed of Glulam members connected using carbon fibre-reinforced composite.

### 2.1 Procurement of Materials

This research employs *Bambusa blumeana*, commonly known as Kawayang Tinik, which is widely acknowledged as the prevailing bamboo species in the Philippines [18]. Fig. 2 illustrates the process of creating Glulam, depicting the sequential stages from selecting bamboo culms to fabrication. The chosen culms for this research were sourced from the Sampaloc region of Manila, with diameters ranging from 50 mm to 80 mm and thicknesses of 5 mm to 8 mm.

The bamboo culms were precisely sectioned into strips measuring  $18 \pm 2$  mm in width and  $6 \pm 2$  mm in thickness. These bamboo strips were submerged in a 6% boric acid solution to prevent potential fungal infestation.

The researcher shaped the dried bamboo strips into the configuration shown in Fig. 3 and applied wood glue to the adjacent sides of the strips. After attaching and allowing the first layer to dry through clamping, the same method was used for the second and third layers until the desired cross-section was achieved. This final cross-sectional pattern of the Glulam aligns with Wu's design, involving the arrangement of bamboo strips in alternating directions [13].

The mechanical attributes of Glulam were derived, and these properties are showcased in Table 1. These mechanical properties were needed to analyse the theoretical behaviour of the space truss, which will be

compared to the experimental results. The mechanical properties of Glubam were determined by ASTM D143-09 – Standard Test Methods for Small Clear Specimens of Timber [17], [19].

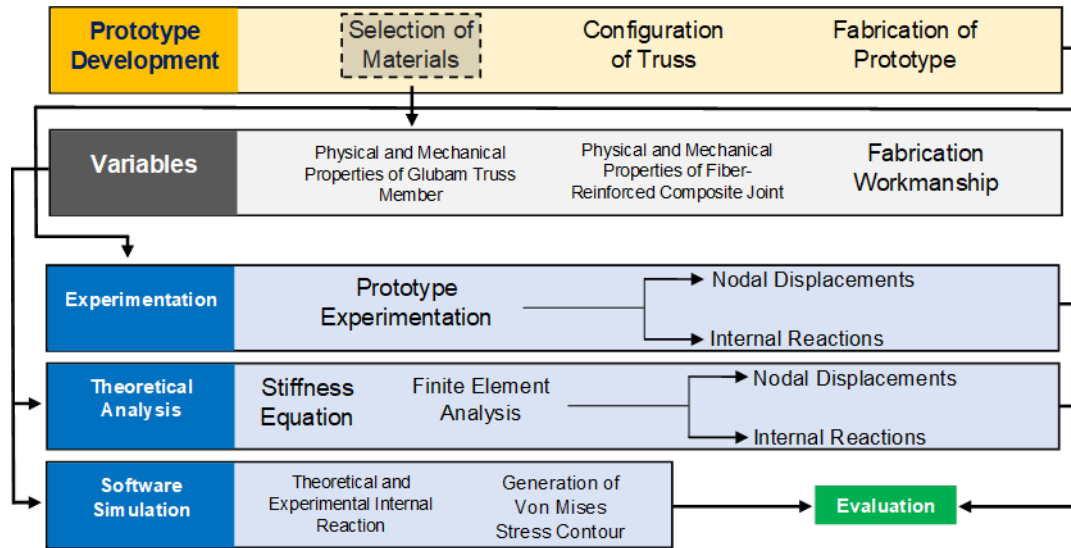


Fig. 1 Research framework

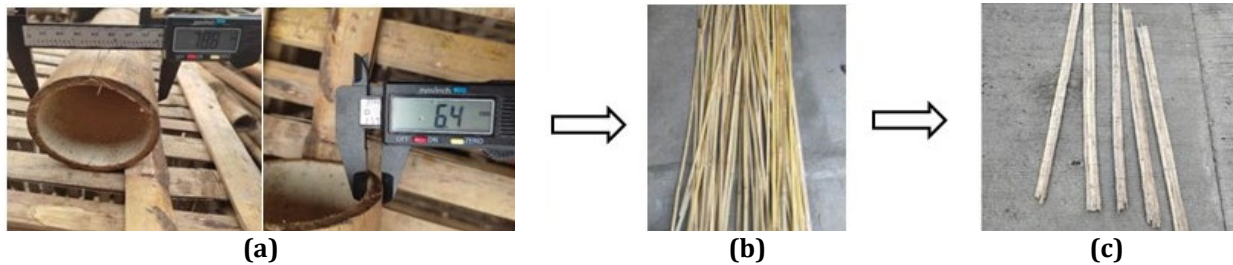


Fig. 2 Procedure for fabricating the Glubam: (a) Selection of bamboo culms; (b) Stripping of bamboo culms; and (c) Fabrication of Glubam

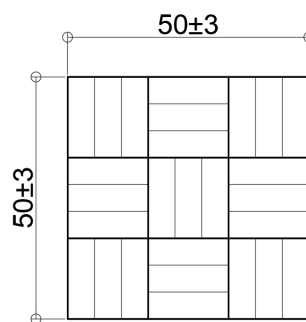


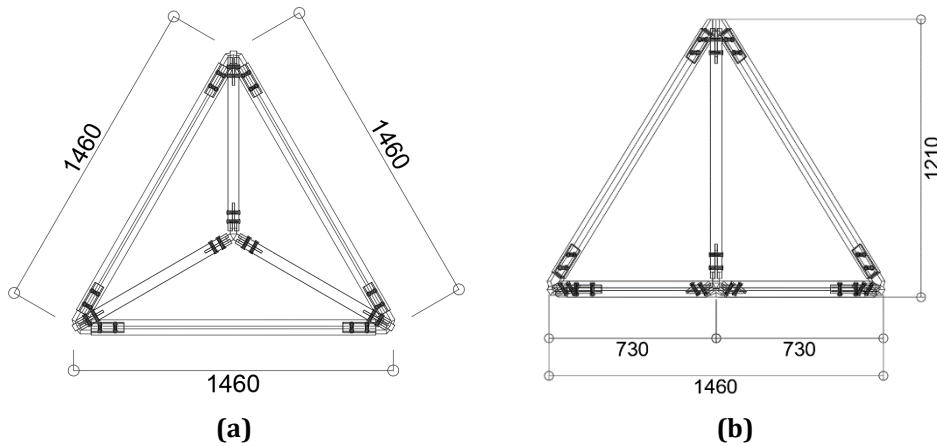
Fig. 3 Configuration of Glubam truss member's cross-section (dimensions in mm)

Table 1 Mechanical properties of Glubam made from Bambusa blumeana

Mechanical Properties	Value (MPa)
Compressive strength	25
Tensile Strength	210
Shearing Strength	16.95
Modulus of elasticity for compression	1862
Modulus of elasticity for tension	37391

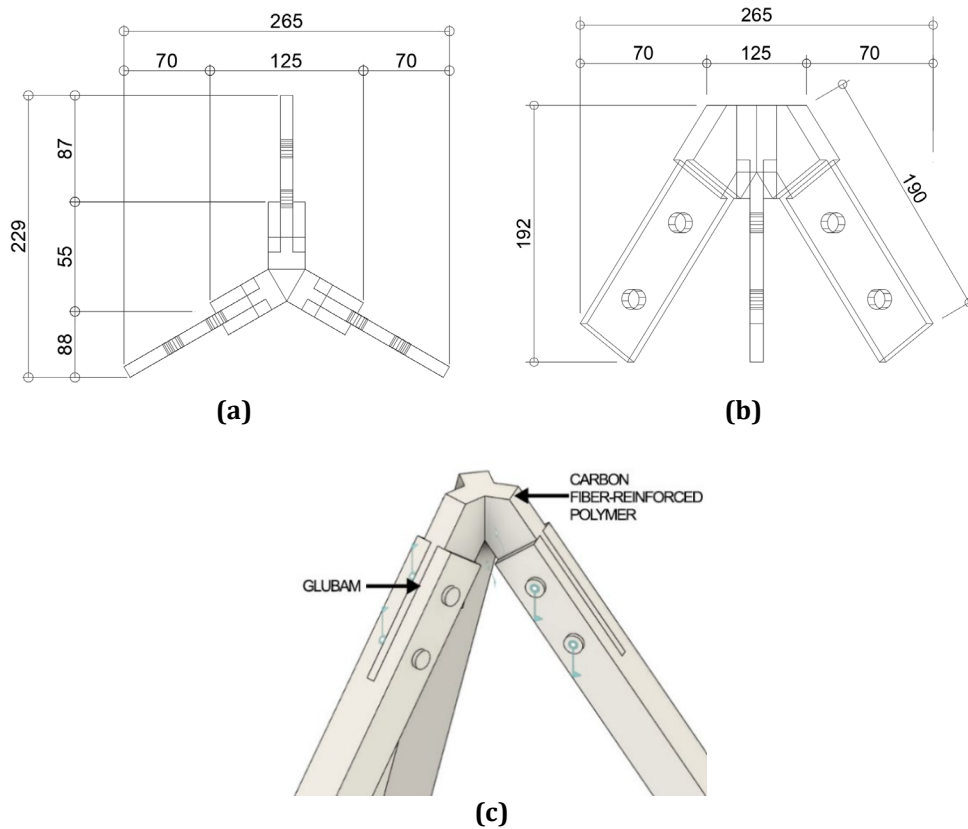
## 2.2 Configuration of Space Truss Prototype

The researcher designed a Glubam space truss prototype, depicted in Fig. 4. Each truss member spans 1.3 meters to create a tetrahedral spatial truss configuration. The front view of the space truss is shown in Fig. 4(a), while the top view is shown in Fig. 4(b).



**Fig. 4** Configuration of Glubam space truss prototype (dimensions in mm): (a) Front view; and (b) Top view

The truss elements are linked through carbon fibre-reinforced composite joints, characterised by the configuration shown in Fig. 5. These composite joints consist of three legs, each connecting three members and featuring two holes for bolts. Additionally, the Glubam truss member includes a slot designed to securely match the leg of the CFR joint, ensuring a snug connection.



**Fig. 5** Geometric design of carbon fibre-reinforced composite joint (dimensions in mm): (a) Top view of CFRP connector; (b) Front view of CFRP connector; and (c) Connection of CFRP to Glubam

## 2.3 Experimental Setup

The construction of the Glubam truss prototype took place within a workshop, providing ample space for arranging the instrumentation tools required to analyse the prototype's behaviour. Two distinct types of instruments were employed for this analysis. To track node displacement, the researcher opted for Light Detection and Ranging (LiDAR), which measures displacement by emitting pulsed laser light and recording the shift in distance between the LiDAR and the observed object. Additionally, strain measurement was achieved using a strain gauge to monitor strain development in the Glubam member during load application. The selected strain gauge features a resistance of  $350 \pm 0.1 \Omega$  and a gauge factor of  $2.0 \pm 1\%$ . The change in resistance allows the strain gauge to measure the strain by employing Eq. (1).

$$\varepsilon = \frac{\Delta R}{R \times GF} \quad (1)$$

where  $\varepsilon$  = Strain in Glubam,  $\Delta R$  = Change in resistance read on a gauge,  $R$  = Initial strain on gauge (taken as  $350 \Omega$ ), and  $GF$  = Gauge factor (taken as 2% or 0.02).

The experimental arrangement is depicted in Fig. 6. In this setup, the truss is positioned such that the node at the apex (Node A) can undergo displacement along the x, y, and z axes, providing it with degrees of freedom. Conversely, the nodes (Nodes B, C, and D) at the base are established as supports, effectively constraining any potential displacement.



Fig. 6 Actual experimentation setup

The schematic diagram for the actual test setup is presented in Fig. 7. Three LiDARs were placed in orthogonal axes that are pointed towards node A. Strain gauges are placed midway along the length of each truss member on opposite sides. A fabric bag is the weight attached to the prototype node. Weight will be added continuously at 98.10 N every three minutes until the load reaches 490.50 N. The LiDARs and strain gauges are connected to a processor. The strain gauges read the strain in members by reading the change in resistance in the strain gauge itself. The change in resistance causes a change in voltage in the circuit where the strain gauge is incorporated. The analog voltage reference reads the change in voltage. The data read by the analog voltage reference will be transmitted to Arduino, where the relationship between the voltage change and strain change will be processed.

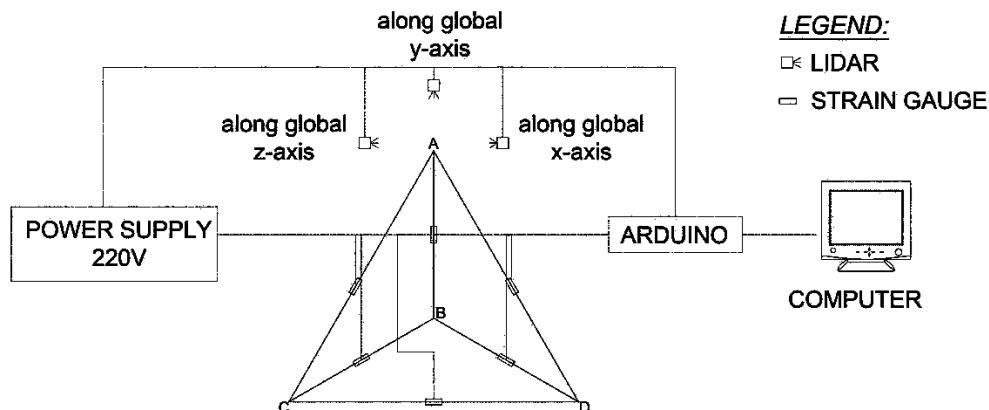


Fig. 7 Schematic diagram of experimentation

Similarly, the LiDARs mounted on the setup read the displacement of the node observed, and the data was transmitted to the Arduino. The Arduino processed the data and transferred it to the computer, where the researcher read the values of nodal displacement and strain in members. The researchers read the members' nodal displacement and strain at every loading interval.

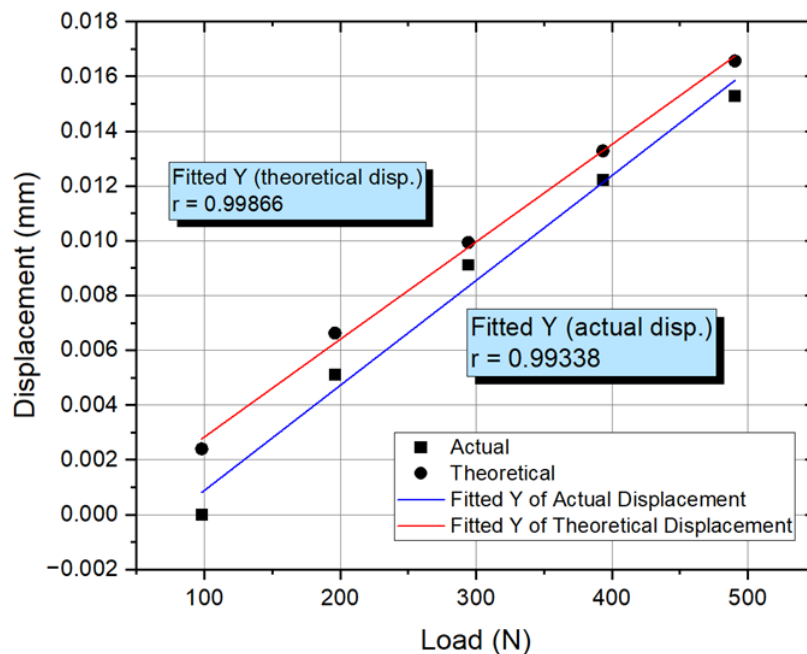
### 3. Results and Discussion

The nodal displacements of joint A obtained from the readings on the LiDAR installed during the actual test setup are presented in Table 2. Displacement at an initial load of 98.10 N was recorded at zero, and a displacement of 0.015 mm was recorded when the load was set at 490.50 N.

**Table 2** Nodal displacement of Node A

Time (minutes)	Load (N)	Nodal displacement of Node A (mm)			
		Global x-axis	Global y-axis	Global z-axis	Resultant Displacement
0	98.10	0	0	0	0
3	196.20	0.000	0.005	0.001	0.005
6	294.30	0.001	0.009	0.001	0.009
9	393.40	0.001	0.012	0.002	0.012
12	490.50	0.002	0.015	0.002	0.015

The load-displacement diagram of the CFRP connector is presented in Fig. 8. The linear regression plot for the theoretical displacement from the study of Lucena has a Pearson correlation coefficient equal to 0.99866, which is very close to 1 [20]. This indicates that the values of displacements are close to linearity. Plotting the actual experimentation results and theoretical results in the same graph, the fitted curve of the actual displacement shows a Pearson correlation coefficient of 0.99338, indicating that the values have high linear strength.



**Fig. 8** Displacement-load diagram of Node A from actual experimentation and computer simulation

The stress values for all Glulam truss components were derived from readings obtained from strain gauges, as presented in Table 3. Notably, under the application of a 490.50 N load, only members AB, AC, and AD exhibited measurable stress values. The structural evaluation, carried out through matrix analysis in Microsoft Excel, revealed that members CB, CD, and BD would not elicit internal reactions due to the vertically downward load applied at node A.

Regarding the stresses at the mid-length points of members AB, AC, and AD—where the strain gauges were strategically positioned—distinct disparities were observed in the stress values. Notably, higher stress values were

evident on the members' inner faces (rear side). The most substantial stress reading recorded was 0.133 MPa, corresponding to member AB.

**Table 3** Stress in Glubam members from the actual test setup

Time (minutes)	Load (N)	Stress in members (MPa)											
		AB		AC		AD		CB		CD		BD	
		Front	Rear	Front	Rear	Front	Rear	Front	Rear	Front	Rear	Front	Rear
0	98.10	0.023	0.023	0.023	0.023	0.020	0.027	0.000	0.000	0.000	0.000	0.000	0.000
3	196.20	0.038	0.047	0.038	0.047	0.035	0.050	0.000	0.000	0.000	0.000	0.000	0.000
6	294.30	0.068	0.069	0.068	0.069	0.066	0.072	0.000	0.000	0.000	0.000	0.000	0.000
9	393.40	0.091	0.091	0.091	0.091	0.088	0.101	0.000	0.000	0.000	0.000	0.000	0.000
12	490.50	0.100	0.133	0.100	0.133	0.099	0.123	0.000	0.000	0.000	0.001	0.000	0.000

#### 4. Conclusions

The study's results revealed that glue-laminated bamboo (Glubam) derived from *Bambusa blumeana* holds potential as a feasible substitute for steel in truss members due to its impressive mechanical properties. The nodal displacement-load curve obtained from practical experimentation and computer simulation displays notable linearity, suggesting that the connector and members exhibit elastic behaviour where stress corresponds to strain. It can be inferred that the connectors will exhibit elasticity before the Glubam attains the proportional limit stress of 59 MPa. This underscores the remarkable potential of Glubam and FRP as materials for truss components.

The study observed that the Glubam cross-section configuration exhibited unfilled voids, which were attributed to the application of wood glue. The unfilled voids cause variability in the cross-section, thereby increasing the non-homogeneity of the material. This results in different strength values from various samples. However, the researcher used the values obtained from experiments from the previous study. To enhance Glubam's strength, it is suggested that a pressing technique be employed on bamboo strips to reduce void formation. Furthermore, there is a recommendation for additional investigations to assess the durability of Glubam in comparison with A36 steel.

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#### Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

#### Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Joe Robert Paul G. Lucena; **data collection:** Orlean Dela Cruz; **analysis and interpretation of results:** Joe Robert Paul G. Lucena; **draft manuscript preparation:** Joe Robert Paul G. Lucena and Orlean Dela Cruz.

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