Comparative Analysis of 3D Steel and Glulam Trusses Using ABAQUS

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Abstract: This study aims at developing an innovative and sustainable 3D truss system that can be applied in a variety of scenarios where intermediary propping is a hindrance. One prominent and pertinent application of such a system is in archaeological sites where long spans and no intermediary propping are desired. Previous research and studies have developed an innovative 3D steel truss for the same application. This study aims to further the innovation by providing a more sustainable alternative through Glulam and Glulam-Bamboo hybrid variations which are able to withstand similar loads as that of the steel truss but offering more sustainability and less impact on the environment as well as a light weight alternative. The results of such an alternative truss system are discussed here. One obvious problem faced with the alternative wood system was the large deflections observed and also certain regions with impermissible stresses. In addition, the proposed joint in the Glulam truss has been modelled and analyzed. It was found that the Glulam truss with lateral restraints at every quarter length of the span showed the best results in terms of deflection and stress developed. Also, the Glulam-Bamboo hybrid truss without any lateral restraints proved to be an equally effective alternative from a structural standpoint. The proposed joint system for the glulam truss also proved to be effective. The study concludes with a cost benefit analysis (CBA) between the steel, glulam and Glulam-Bamboo hybrid systems, which compares the viability of the proposed designs from an economic standpoint. The CBA shows that about 46% and 48% of costs are minimized on employing Glulam, Glulam-Bamboo respectively, instead of using Steel for the truss.

Keywords: sustainable, glulam, bamboo, hybrid systems

1. Introduction
Sustainability revolves around reducing carbon footprint of our current construction activities and expanding accessibility of sustainable habitation to all. Using timber in construction is valued in the creation of a sustainable environment, due to wood’s capability of carbon sequestration. Although steel, iron and concrete being the more popular choice of construction material, they have raised serious concerns about the carbon footprints, over the last century. This has ultimately led to a change towards timber as a potentially plentiful and sustainable structural material for a wide range of applications in building construction. Advanced adhesives, preservatives and fire protection have made possible to manufacture engineered timber products such as glue – laminated timber (Glulam). Such products are more predictable and stable in their properties, and so structures can be designed and analyzed with a higher degree of precision, for resilient and predictable performance.
This study is tailored towards the creation of a more sustainable alternative for a protective structure designed for the preservation of a typical archaeological site, by addressing the general needs of such a structure. [1] have conducted investigations involving design of new steel 3D trusses for preserving archaeological sites. A constructive system adopted for covering a composite structure made of primary steel 3D lattice beams and glass slab, has been specifically designed for safeguarding archaeological and cultural heritage sites. The beams are placed parallel to each other at a given distance, without intermediate supports, to form the primary structure of the coverage.

A sustainable alternative to weathering steel, is Glulam. Investigation of this material, has been extensively pursued, in order to show its aesthetically pleasing and structurally robust qualities. A study conducted by [2], show that steel beams are more prone to lateral torsional buckling than Glulam beams of similar cross sections. In the construction of trusses, an important factor that will determine if it is serviceable, is the deflection of the truss in response to loading. Timber beams are more sensitive to deflection as the beam span increases, in contrast to the case of steel beams. Lateral supports or restraints can be used to decrease the deflection, or glulam beams can be produced with a camber, to bend or curve upwards at the center. Another way to reduce the deflection is by increasing the dimensions of the Glulam sections. The dimensions of the Glulam beams are considerably larger than the dimensions of the steel beams for the same span, and may not always be a feasible solution in reducing the ensuing deflection [2].

Due to this caveat of Glulam, another sustainable material, such as Bamboo, could also be considered to remediate any excess deflection. Bamboo is a fast-growing type of grass. [3] confirmed that it has high strength to weight ratio, about six times higher compared to steel; it reaches its optimum strength in 3–4 years and attains complete maturity in 5 years. Bamboo is a highly-yield renewable resource. They can be harvested within 3–5 years unlike most softwood 10–20 years [4]. Due to its high strength to weight ratio, the bamboo truss shows satisfactorily low deflection even without lateral restraints. Although the Bamboo material may exhibit various advantages, it may be not be plausible to completely replace it with Glulam, owing to its hollow profile and shape constraints posed during construction of complex parts in the proposed model. This induces a Bamboo-Glulam hybrid structure, which is a culmination of the advantages of both materials.

Glulam joints, are to be carefully chosen according to the use, and location of the structure. Principally, the strength, stiffness, ductility and corrosion are the basic criteria to consider in the selection of a connection for a Glulam truss [5]. Based on these criteria, a connection with slotted-in steel-plate and dowel type fasteners is feasible in order to achieve a connection with high force transfer capacity, ease of installation, configuration flexibility, functional performance, and cost effectiveness. The slotted-in type of connection is considered as a reliable solution and has been applied in straight and arched long-span glulam trusses for sport arenas, exhibition halls, airports, and timber bridges [6]. The proposed bamboo joint, on the other hand, consists of bamboo rods linked to plywood plates, with additional pine timber cylinders as reinforcements, necessitated due to bamboo’s hollow profile [7].

The truss beams are surmounted by structural laminated glass panels which will form the primary structure of the coverage. Transparent material is frequently preferred in the design of facade cladding and roof. The motivation of this attitude can be associated with criteria concerning maintenance, construction, visual impact and display [8]. The glass panels must be connected with the wooden frame in a way that prevents stress peaks and ensure a uniform force transmission from the structure to the glass [9]. In order to reach a good product performance, the two materials shall be mounted together in a static sense by using appropriated adhesives. This method for transferring stresses,
i.e. adhesion, is preferred to the mechanical fastening of glass to ensure a certain amount of deformability within the panel [10]. Elastic adhesives, e.g., silicone, is a suitable adhesive for connecting the Glulam members and glass panels, since it is highly flexible, demonstrates good resistance to moisture and shows the highest UV resistance among all the adhesives.

Glulam beams are the most environmentally friendly option, and the carbon-storage capacity of the wood ensures that using such beams have a positive impact on the greenhouse effect and therefore the environment. The dry mass of wood is 50 per cent carbon, and this carbon is removed from the atmosphere, which mitigates the climate change caused by the greenhouse effect. This is not the case in steel [2]. When Glulam is used as a structural beam in buildings, it is required to have high durability in order to retain the imperative strength to ensure that the structural skeleton of the construction is maintained. Glulam structures have a lifetime of 100 years, while untreated steel structures have a lifetime period of about 50 years [11]. Practical experience of constructing Glulam structures has shown its high durability efficiency in chemically aggressive environment.

This paper investigates the use of sustainable alternatives to structural steel, such as Glulam and Bamboo for the protection of archaeological sites through a protective structure such as a truss, through finite element analysis which will provide a cheaper and faster option as to conventional testing, for analyzing the behavior of the structure.

2. Research Significance
A prime example of a scenario where there is requirement of a protective structure, without the need for any secondary members, are the protective structures for archaeological sites. Sheltering an archaeological site is an advantageous measure in preserving the site and making it accessible to the public. Archaeological sites are very vulnerable sites in need of protection from the environment. A typical shelter is lightweight, able to cover large spans without intermediate supports and ensure accessibility to assets. It should also be easy to assemble, maintain, disassemble and possibly reusable in other sites. [1] have proposed a steel 3D truss system for the same aforementioned purpose. This study aims to bring in a similar 3D truss system with additional aspects of being light-weight as well as more sustainable. Hence, the objectives of this study include to:

- Develop an innovative design of the conventional steel truss with a Glulam substitute and Glulam-Bamboo hybrid substitutes for purposes of preservation of archeologic sites, alongside promoting sustainable development and economic efficiency.
- Ensure optimum efficiency of the new wooden model as compared to that of the steel counterpart.
- A comparative cost – benefit analysis between the steel and Glulam model to reiterate benefits of the Glulam substitute.

3. Methodology and Analysis
3.1 Steel Truss
The proposed 3D steel truss is borrowed from the design of an innovative 3D truss for preserving archaeological sites [1]. The purpose of this steel truss is to be used as a template to model a wooden truss with similar properties and resilience for the aforementioned advantages. The RHS profile is longitudinally cut in two hemi-profiles subsequently assembled through welded tie plates, which allow for suitably distancing the hemi-profiles, as shown in Figure 1. The bottom chord is made of hot-rolled round (R) or square (SQ) profiles, or even, in case of very long trusses, of Square Hollow Section (SHS) members. The bottom chord nodes are designed as fully rigid joints and they are stiffened with plates.
having thickness ($t_f$) close to that of top chord members. Finally, web members are made of R bars or Circular Hollow Section (CHS) profiles. Figure 2 shows the overall view of the proposed roof.

3.1.1 Modelling
The modelling of the truss was done using ABAQUS. The length of the truss system is 15m (short span). Accordingly, the cross-section and size of the bottom, diagonal and top chords are obtained from Table 1.

![Figure 1](image1.png)  
*Figure 1. Net C-RHS profile of truss [1]*

![Figure 2](image2.png)  
*Figure 2. Pictorial view of proposed roof [1]*

Table 1. Abacus of beams resulted from the design process [1] (Highlighted portion shows the selected profiles)

| Designation | Acronym         | Basic profiles | Bottom chord | Diagonal chord |
|-------------|----------------|----------------|--------------|---------------|
| Beam family |                | Top chord      | Hot rolled steel bars or Square Hollow Section | Hat rolled steel bars or Circular Hollow Section |
|             |                | Cold formed hollow profiles |               |               |
|             |                | Weight per unit length [kNm] |               |               |
| Short       | BB.CC_600x4    | 0.59 | RHS200x100x4 | R38 | R30 |
|             | BB.CC_600x5    | 0.65 | R11S2C0x100x5 | R42 | R30 |
|             | BBCC_600x6     | 0.75 | RHS200x100x6 | R46 | R32 |
|             | BB.CC_600x63   | 0.76 | RH5200x100x6,3 | R47 | R32 |
|             | BB.CC_600x8    | 0.91 | R52          | R52 | R36 |
|             | BB.CC_600x10   | 1.04 | RHS200x100x10 | R58 | R36 |
|             | BB.CC_600x12.5 | 1.19 | RHS200x100x12.5 | Rb3 | R38 |
| Medium      | BB.CC_900x6    | 1.09 | RHS 300x150x6 | SQ50 | R40 |
|             | BB.CC_900x6,3  | 1.15 | RHS 300x150x6,3 | SQSS | R40 |
|             | BB.CC_900x8    | 1.39 | RHS 300x150x8 | SQ60 | R44 |
|             | BB.CC_900x10   | 1.66 | RHS 300x150x10 | SQ65 | R48 |
|             | BB.CC900x12    | 1.87 | RHS 300x150x12 | SQ70 | R50 |
|             | BB.CC_900x12.5 | 1.95 | RHS 300x150x12.5 | SQ7S | R50 |
| High        | BB.CC_900x16   | 2.34 | RHS 300x150x16 | SQ80 | R55 |
|             | BB.CC_1200x8   | 1.46 | RHS 400x200x8 | SHS 200 x 6 | CHS 1143 x 3 |
|             | BBCC._1200x10  | 1.86 | RHS 400x200x10 | SHS 200 x 8 | CHS 1143 x 4 |
|             | BB.CC_1200x12  | 2.33 | RHS 400x200x12 | SHS 200 x 10 | CHS 1143 x 6 |
|             | BB.CC_1200x12.5 | 2.37 | RHS 400x200x12.5 | SHS 200 x 10 | CHS 1143 x 6 |
|             | BB.CC 1200x16  | 2.94 | RSH S 400x200x16 | SHS 200 x 12 | CHS 1143 x 8 |
Table 2. Dimensions of selected Octagonal Openings [1]

| Opening parameter | Initial hexagonal opening height | Hexagon width | Batten plate length | Final opening height (octagonal) | Distance between two openings |
|-------------------|-------------------------------|----------------|-------------------|----------------------------------|------------------------------|
| h' [mm]           | Lh [mm]                       | bh             | aopt [1mm]        | h' [mm]                          | w [mm]                      |
| 200               | 115                           | 231            | 300               | 500                              | 69                           |

The truss in the ABAQUS model is divided into two parts: bottom and diagonal chords and the top chord. It is modelled according to the dimensions from Table 1. and Table 2. The properties and the interactions between the two parts, along with the boundary conditions (BC) are appropriately modelled. Two uniform pressures are applied in the form of dead load (DL) and live load (LL). As per Lorenzo et. al. [1], typical loads to expect in such truss systems are:

1. Dead Loads (DL) – [0.25, 1kN/m²]
2. Live Loads (LL) – [1,3kN/m²]

The higher loads of DL=1 kN/m² and LL=3 kN/m² are adopted in the simulation. An arbitrary mesh size of 100mm is chosen. Once the above steps are complete in an error free manner, the model is submitted for analysis and the results are displayed. Glulam material, unlike steel, is an anisotropic material, and experiences linear elastic brittle tensile failure [12]. The glulam truss is modelled the same way as the steel counterpart with the only exception of the material property of glulam (shown in Table 3) replacing the steel property. Glulam Spruce softwood of a homogeneous composition, GL24h, has been selected, and is curated to fit the intended purposes of an exposed roof beam structure.

Table 3. Engineering Properties of Glulam [13]

| Property Number | Property       | Value | Unit   |
|-----------------|----------------|-------|--------|
| 1               | Elastic Moduli | E1    | 600    | MPa    |
| 2               | E2             | 600   | MPa    |
| 3               | E3             | 12000 | MPa    |
| 4               | 𝜐1            | 0.558 | -      |
| 5               | 𝜐2            | 0.038 | -      |
| 6               | Poisson’s ratios | 𝜐3     | 0.015  | -      |
| 7               | Shear Moduli   | G1    | 40     | MPa    |
| 8               | G2             | 700   | MPa    |
| 9               | G3             | 700   | MPa    |
| 10              | Density        | ρ     | 430    | kg/m³  |
| 11              | Bending Strength | fo    | 24     | N/mm² |

3.2 Glulam Connections

Steel- to timber dowel joints are commonly used for Glulam trusses of varying span. The joint is easy and fast to assemble. In addition, mechanical joints allow the Glulam members to generate ductile failure. Since the proposed structure is an exposed structure and is subject to a risk of wetting, using an embedded connection such as the slotted steel plates and dowels, makes it unexposed to external moisture. Below a threshold moisture content of 15%–18%, embedded metals do not corrode, [14]. Moreover, the presence of slots in the steel plate, facilitates internal moisture transport. This study explores the stability of such a connection, by modelling a single joint on the bottom cho
The bottom and diagonal chords were modelled according to the dimensions given in Table 2, and material properties from Table 3. Two slotted in steel plates are used at each node, by adopting the dimensions as shown in Figure 3. The dowels are responsible for load transfer between the plates and the Glulam members, and are of 6.02mm diameter and 10mm length. The Dowels and Slotted Steel plate are made of S355 Steel whose properties are given in Table 4. The two slotted in steel plates are joined at an angle of 70° between them. This is assembled in such a way that the plates remain embedded within the bottom and diagonal chords. Dowels are inserted appropriately.

Contact phenomena between steel and wood were modelled by defining pairs of master and slave contact surfaces in ABAQUS for the dowels. Small sliding surface-to-surface discretization method was considered for all the contacts. The surface contact properties between the dowels and plate were modelled with tangential behavior using penalty friction with the friction coefficient value of 0.3 [15]. Additionally, the slotted in steel plate is given an embedded constraint.

Table 4. Properties of Dowels and Slotted in Steel Plate

| Property            | Value     |
|---------------------|-----------|
| Density             | 7850 kg/m³ |
| Young’s Modulus     | 210000MPa  |
| Poisson’s Ratio     | 0.3       |

Table 5. Mises Stresses recorded for the Bottom and Diagonal Chords from ABAQUS

| Part Instance      | Element ID | S, Mises (N/mm²) |
|--------------------|------------|------------------|
| Bottom Chord       | 23         | 3.72521          |
| Bottom Chord       | 12         | 3.34562          |
| Diagonal Chord 1   | 225        | 382.047E-03      |
| Diagonal Chord 2   | 560        | 200.656E-03      |
| Diagonal Chord 3   | 205        | 397.11E-03       |
| Diagonal Chord 4   | 200        | 183.963E-03      |
Two different types of loads are applied:

(i) **Dowel Pretension.** Dowels having yield strength of 700 MPa are chosen. Pretension load level is 80% of Yield strength i.e., 560 MPa. The pretension force magnitude (15833.6N) is chosen based on the effective cross area of the bolt shank in order to inflict a stress of 560 MPa (80% of yield) upon the bolt.

Bolt Loading is applied in 3 steps: *Initial Step*. Boundary condition; *Step 1*. Bolt preloading/activating the contact element; *Step 2*. Fixing the bolt length; *Step 3*. External load.

The dowels are preloaded in the first step of the analysis. The pretension is simulated by splitting the dowel body and applying a magnitude of preload force on two parallel surfaces in the shank. After applying the pretension to the dowels, their length is fixed at their current position. During the first two steps (Initial Step and Step 1), all three translational degrees of freedom at the section of pretension are restrained [16].

(ii) **External Loads.** In *Step 3*, the external loading is applied. Stresses experienced by the members are derived from ABAQUS. Table 5. shows that the bottom chords experience an average stress of 3.5 N/mm² while the diagonals experience an average stress of about 0.3 N/mm². An average stress of 0.5 N/mm² is applied on the diagonals, and 3.5 N/mm² on the bottom chord. On the two right diagonals, a tension of 3.5 N/mm² is simulated by the use of boundary conditions.

**4. Results and Discussions**

**4.1 Steel 3D Truss**

The stress distribution contours (in N/mm²) obtained for the steel 3D truss are shown in Figure 4. The maximum stress built up in the truss is only around 40 N/mm², which is within the permissible yield stress limit of 333 N/mm². As per IS 800:2007 [17], the serviceability deflection limit, should not normally exceed span/240, which in this case comes to 62.5mm. The displacement contours of the steel truss display a maximum deflection of 26mm at the Centre.
4.2 Glulam 3D Truss
This truss is structurally the same as the steel counterpart. All the materials have been changed from steel to Glulam properties to arrive at this alternative. It is identified that the bottom chords are under compression (indicated by negative stress values). The diagonal chords angled towards the left are also in compression while the ones angled towards the right are in tension (positive stress values). While the top chord is modelled as a shell, it is seen to undergo tension in the Centre and compression in the ends, thus indicating a bending mode of stress. The permissible stress in bending, tension and compression for the chosen Glulam material is shown in Table 6 [18]. As shown in Figure 5, stresses of around 2-7 N/mm² are developed in the top portion of the top chord, which is within the permissible value of 16 N/mm². Inspecting the bottom and side portions of the top chord, higher stresses of 12-17 N/mm² are seen to be developed, which is still within the permissible number but few spots have been seen to develop 20 N/mm² which is impermissible but still within the yield value of the material.

Table 6. Permissible stress values for Glulam GL24H material [18]

| Stress Type | Characteristic Stress (N/mm²) | Permissible Stress (N/mm²) | Factor of Safety |
|-------------|-------------------------------|----------------------------|------------------|
| Tension     | 19.2                          | 10.66                      | 1.8              |
| Compression | 24                            | 17.14                      | 1.4              |
| Bending     | 24                            | 16                         | 1.5              |

Figure 4. Close up view on the Centre of the truss with stress contours (stress in N/mm²)

Figure 5. Stress distribution contours in the Glulam 3D truss
Excessive deflection was noticed while observing the deflection contours of this model, as shown in Figure 6. At the center, about 550mm of deflection is noticed, which is impermissible. The recommended range of limiting values of deflections for beams with span L, for simply supported timber beams is given as L/150 to L/300 according to Eurocode 5 [19], which results in a range of 50mm to 100mm. This deflection is commonly observed in all wooden structural elements. Deflection increases with increase in span.

![Figure 6. Deflection contours of Glulam truss (deflections in mm)](image)

4.3 Alternative Solutions

4.3.1. Lateral Restraints. Provision of lateral restraints have been explored as a viable possibility to mitigate the excessive deflections caused in the truss system. This is simulated by fixing a fixed support boundary condition at every quarter length of the span. This boundary condition is fixed on the area at the side of the top chord. The maximum deflection developed here is only around 20 to 24 mm (green regions of the truss), as shown in Figure 7 which is within the permissible deflection of 60mm. Also, the stress values developed throughout this model, are well within the permissible values in bending, tension and compression.

![Figure 7: Deflection contours of Glulam model- lateral supports at every quarter of the span](image)

4.3.2 Glulam-Bamboo Truss. Another alternative solution to the excessive deflection has been considered. A bamboo- cum-Glulam truss has been proposed, to alleviate the problem of a large deflection observed in the Glulam model. To this end, the bottom chord and the diagonal chords have
been modelled as bamboo parts, since it shows better deformation ability and ductile behavior under compression than wood [20] and also remains another widely used sustainable option in construction. As shown in Figure 8, the stress contours developed in the model does not come near the allowable stresses (Table 7) of the chosen bamboo material.

**Table 7. Permissible stress values for chosen Bamboo material [21]**

| Stress Type | Characteristic Stress (N/mm²) | Permissible Stress (N/mm²) | Factor of Safety |
|-------------|-------------------------------|---------------------------|-----------------|
| Tension     | 193                           | 107.22                    | 1.8             |
| Compression | 68.4                          | 48.86                     | 1.4             |
| Bending     | 62.86                         | 41.91                     | 1.5             |

![Figure 8: Stress distribution contours for the Glulam-Bamboo truss, close up view with adjusted contour limits](image)

![Figure 9: Deflection distribution contours for the Glulam - bamboo model](image)
The deflection observed is 60mm, as shown in Figure 9 at the centre with the bamboo section, which is within the allowable limits for deflection of any timber structure (50-100mm is allowable deflection [19]).

4.4 Glulam Connections

4.4.1. Stresses. The stresses on the dowels at the center, where the load is applied, shows 487 N/mm$^2$, as seen in Figure 10. The inner halves of the dowels exhibit tension, while the outer halves go through compression. The slotted in steel plate on the other hand, undergoes stresses of 23 N/mm$^2$, on its bottom half as shown in Figure 11. The upper half of the plates show stresses of almost 0 N/mm$^2$. Figure 12 and 13 show the stresses exhibited by only the exterior glulam members. As can be seen in Figure 12, the majority of the members show very low stresses, of almost 0 N/mm$^2$, with the ends of the bottom chord showing a maximum of 15 N/mm$^2$. Figure 13 shows the regions in tension i.e.; the two right diagonals and few regions on the bottom chord, ranging between tensile stresses of 0.08 and 0 N/mm$^2$. The regions in compression are in black, i.e.; ends of the bottom chord and the two left diagonals, showing a compressive stress of 0.6 N/mm$^2$.

4.4.2. Displacement. The dowels show no displacement, owing to the applied boundary conditions and loading. The plates show almost 0mm displacement at the center and 0.008mm on the bottom half, as
can be seen on Figure 14. This proves the connection to be stable, since it shows no excessive deflections. Figure 15. shows the two right diagonals, showing a displacement of 0.1 mm, owing to the applied loading and boundary conditions. The other regions of the outer glulam members show a negligible displacement of 0 mm. The preloading of the dowels is done to simulate that the dowels are loaded to its maximum tension before external loading can be applied. This will enable the dowels endure significantly higher external loading, without slip, rendering the plates and the external Glulam members to withstand the applied loading and making the entire connection stable.

5. Cost – Benefit Analysis

A cost-benefit analysis (CBA) is the process used to measure the benefits of a decision or taking action minus the costs associated with taking that action. It involves measurable financial metrics such as revenue earned or costs saved as a result of the decision to pursue a project. It can also include intangible benefits and costs or effects from a decision such as employee morale and customer satisfaction. The intangible benefits of this model, have been denoted here by a 5-star rating system, as shown in Table 9.

Note – The costs are rounded approximations of their calculated estimates

5.1. Costs – Accounting for 100 years

Table 8. CBA part 1

| PROJECT PARAMETERS | STEEL TRUSS | GLULAM TRUSS | BAMBOO-GLULAM TRUSS |
|--------------------|-------------|--------------|---------------------|
| Time Of Completion | 1 YEAR      | 1 YEAR       | 1 YEAR              |
| Raw Material       | 66 lakhs    | 26 lakhs     | 36 lakhs            |
| Manufacturing/     | 11 lakhs    | 80 thousand  | 94 thousand         |
| Processing         | (1 lakh app.) | (1 lakh app.) |                     |
| Erection Cost (Rs.)| 7 lakhs     | 5 lakhs      | 5 lakhs             |
| Labour Cost (Rs.)  | 109 lakhs   | 146 lakhs    | 146 lakhs           |
| Design Life        | 50 YEARS    | 100 YEARS    | 100 YEARS           |
| Maintenance (Rs.)  | 2 lakhs     | 2 lakhs      | 2 lakhs             |
### 5.2. Benefits - Accounting for 100 years

#### Table 9. CBA part 2

| PROJECT PARAMETERS | STEEL TRUSS | GLULAM TRUSS | BAMBOO GLULAM TRUSS |
|--------------------|-------------|--------------|---------------------|
| MAINTENANCE COSTS SAVED | -           | 2 lakhs      | 2 lakhs             |
| TOTAL EXPENDITURE SAVED | -           | 211 lakhs    | 201 lakhs           |
| DURABILITY         | ***         | *****        | ****               |
| STRENGTH TO WEIGHT RATIO | ***       | ****         | ****               |
| EASE OF CONSTRUCTION | ****       | ****         | *                  |
| ENVIRONMENTALLY FRIENDLY | **       | ****         | ****               |
| HEALTH ASPECT      | ***         | *****        | *****              |
| AESTHETICALLY PLEASING | ****     | *****        | ****               |

**Figure 16:** Comparison of various costs of steel, glulam and Glulam-Bamboo models
5.3 Results of Cost – Benefit Analysis

The project parameters taken into consideration and their expenses have been mentioned in Table 8. The most significant costs, account to be that of Raw material and labor as shown in Figure 16. About 46% and 48% of costs are minimized on employing Glulam and Glulam- Bamboo respectively with respect to conventional steel truss, as depicted in Figure 17. The design life of steel truss is only half that of timber, hence a complete reconstruction of steel structure is required after 50 years. Hence the cost of steel per 100 years is doubled whereas Timber stands strong for the same duration. The total cost of steel truss accounting for 100 years is 54% higher than Glulam and 52% higher than Glulam- Bamboo. Additionally, Strength to weight ratio of bamboo is 6 times higher than steel and is similar to that of Glulam. Hence the Glulam and Glulam-Bamboo truss receive similar ratings and are both rated higher than the steel truss.

Both Glulam and Glulam- Bamboo models are very environmentally friendly, contributing to reduction in the carbon footprint. On average about 1.9 tonnes of CO₂ is produced for every tonne of steel produced. Timber manufacture too, contributes to the carbon footprint, however it remains lower than that of steel. Timber beams are the most environmentally friendly option, due to the carbon- storage capacity of the wood. Additionally, on ensuring that the wood is reclaimed at the end of its lifetime, timber’s CO₂ emissions are kept to a minimum. Both Glulam and Glulam- Bamboo trusses are better options compared to the traditional steel trusses in terms of being environmentally friendly, health aspects and economic efficiency. It is a greener equivalent to the steel truss; between the two alternatives it can be concluded that the Glulam truss is a better alternative. This is due to the increased durability of Glulam truss over the Glulam- Bamboo truss, a 6% increase in costs of Glulam-Bamboo over the Glulam truss, aesthetically pleasing nature of Glulam over Bamboo, and due to the ease of construction of the Glulam truss as compared to Bamboo.

Hence the cost- benefit analysis concludes that the Glulam model is the best choice as it supersedes the others in terms of structural stability, environmental aspects and economic efficiency.

Figure 17: Bar chart comparing the total costs of steel, glulam and Glulam-Bamboo models

NOTE: All data (including the star rating system (out of 5) relating to the above analysis were obtained from Petrofac PVTLTD and Winmeen Engineers PVTLTD.
6. Conclusions

This study aims at developing an innovative and sustainable 3D truss system that can be applied in a variety of scenarios where intermediary propping is a hindrance. An innovative 3D steel truss from recent literature was chosen for this purpose and modelled on ABAQUS. Using this as a template, a replica of the same model but with Glulam elements was modelled. However, this model faced impermissible deflections and subsequent model iterations were generated. Based on the analysis and study conducted, the following conclusions can be made:

Glulam truss with lateral supports at every quarter of the span displayed the least deflection values. This solution is successful in reducing the initial deflection by up to 96%, thus bringing it well within permissible values. Glulam-Bamboo hybrid truss with bamboo alternatives for the diagonal and bottom chords and glulam top chord but without any lateral supports showing comparable performance with that of glulam truss with lateral supports is also presented as an alternative solution. This newly developed Glulam-Bamboo truss is successful in reducing the deflection by 89%.

In addition to reviewing the Glulam truss, the Glulam connections are also numerically analyzed. A slotted-in-steel plate with dowels connection has been chosen. This connection shows permissible deflections and stresses, upon conducting analysis. Thus, the connection is structurally feasible, and is also a viable solution to remediating the deflection of the Glulam truss.

The study concludes by performing a Cost benefit Analysis, to highlight the economic efficiency of the two trusses and the solutions proposed. The CBA shows that about 46% and 48% of costs are minimized on employing Glulam, Glulam- Bamboo respectively, instead of using Steel for the truss. Among these, the Glulam model is the best choice as it supersedes the others in terms of structural stability, environmental aspects and economic efficiency.

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