WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

IMPROVING BENDING PERFORMANCE OF HYBRID STRUCTURE WITH GLUED LAMINATED TIMBER AND STEEL TENSION BAR

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ABSTRACT: Timber construction is gaining attention as an alternative for achieving the 2050 carbon neutrality goal, given its carbon storage capability and lower greenhouse gas emissions compared to reinforced concrete constructions. To expand the application of timber construction, structural timber members applicable to various architectural designs must be developed. This study analyzed the performance and behavior of hybrid inverted king-post timber trusses under bending loads based on the characteristics of their members. The hybrid inverted king-post timber truss demonstrated performance domparable to or exceeding than the conventional glued laminated timber (GLT), despite having half the cross-sectional area of the GLT. The hybrid inverted king-post timber truss, with higher quality of steel and increased diameter of the tensile member, exhibited the highest values in terms of maximum load, modulus of elasticity (MOE), and modulus of rupture (MOR), confirming its potential for use as a structural material. When utilized as a structural component to support bending loads, it is expected to significantly improve forest resource efficiency by reducing timber usage and enhancing spatial efficiency in buildings. The hybrid truss maximizes performance by designing the system to distribute the loads acting on the entire structure appropriately across each member and ensuring each member is capable of supporting the maximum load applied to it. This study particularly suggests the feasibility of using hybrid timber trusses combining structural glued laminated timber made from domestic small-diameter timber for large-scale and high-rise timber buildings requiring high load-bearing capacities.

KEYWORDS: glued laminated timber, hybrid inverted king-post timber truss, flexural performance, steel tension bar, timber construction

1 – INTRODUCTION

The use of wood as building materials, which is a carbon storage, is becoming important worldwide to achieve the goal of reducing greenhouse gas emissions in the construction sector. In particular, wood-based building materials consume less energy in the manufacturing, processing, and transportation than cement and iron, which are building materials widely used. Wooden architecture is known to have the advantage of mitigating climate change with low carbon emissions. Structural materials used in timber construction must be able to predict their load support performance, and based on this, it is possible to design the structure.

Large or high-rise wooden buildings require large-span beams or large dimension columns. With the development of structural engineered wood having an enlarged cross-section and length, large-scale and high-rise wooden buildings have become possible. Representative structural engineering wood is structural glued laminated timber

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https://doi.org/10.52202/080513-0525

(GLT) and cross laminated timber (CLT). Improving the strength performance of structural engineered wood is essential to expand the design freedom of wooden architecture.

In order to complete a classroom or auditorium that needs a long span, a bending resistant member or system that supports the bending load over the span is required. The bending members used for a long span are generally designed by increasing the cross section of the material. However, there are some cases in which the height of the bending member cannot be increased as desired due to the cost or the aesthetics issues of the building. In addition, there are cases where the required bending performance cannot be achieved with structural engineered wood. In this case, the required performance can be achieved by a hybrid structure of other materials and wood. Therefore, it is necessary to build a bending support structure by a hybrid structure.

A hybrid structure suitable for supporting a large load in a long span can be designed in combination to demonstrate the advantages of wood and steel. The hybrid structure has the advantage of being able to expand the span, reduce the cross-sectional area of the structure, and be designed in various shapes.

In this study, the possibility of replacing GLT with large cross-sections by an hybrid inverted king-post timber truss system with wood and steel was examined. In addition, by analyzing the stress concentration and load supporting mechanism of the hybrid inverted king-post timber truss as the load increases, it was performed to improve the load support performance based on a quantitative evaluation of the load support performance of the truss system.

2 – MATERIALS AND METHODS

2.1 DESIGN OF HYBRID INVERTED KING POST TIMBER TRUSS

The GLT top chord in the hybrid inverted king-post timber truss was used to support only the compression load, and the steel tension bar as bottom chord was to support tensile load. It was designed in the form of an inverted triangular truss supporting the bending load (Fig. 1). The connection point of the truss was assumed to be a pin joint. According to the size of the concentrated center load and the length of the central vertical post material, the compression load of GLT top chord and the tensile load of steel bottom chord were calculated by the truss analysis method.

The design load of the truss system (73.5 kN) was calculated as the same design load of GLT (10S30B grade, 150Ｘ150 ㎜) by KS F 3021(Korean Agency for Technology and Standard). Table 1 shows the calculation results of the member force at this time.

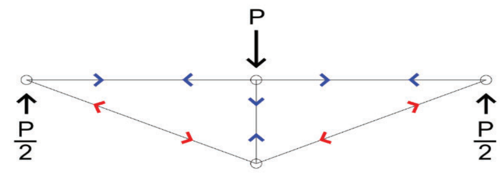

Figure 1. Load distribution in the inverted king-post truss

Table 1: Applied forces on the members of the inverted king-post truss under the central load

Vertical web height (mm)	*P (kN)*	*Top chord (kN)*	*Bottom chord (kN)*	*Vertical web (kN)*
150	73.5	(-)515.2	(+)516.5	(-)73.5
300	73.5	(-)257.3	(+)259.9	(-)73.5

(-): compressive stress, (+): tensile stress

2.2 MATERIALS

GLT was manufactured from domestic larch (*Larix kaempferi*). For GLT, four laminates of E11 grade were used to manufacture 10S34B grade GLT according to KS F 3021 with a Phenol Resorcinol Formaldehyde (PRF) resin application amount of 250 g/m2 and a pressing force of 12 kgf/cm2.

Table 2: Glued Laminated Timber (GLT) specification

Specimens	*Species*	*Size(mm)*	*Number of Layers*
GLT(control)	*Larix kaempferi*	140Ｘ150Ｘ4460	4
A (15)		140Ｘ75Ｘ4200	2
B (30)			

https://doi.org/10.52202/080513-0525

Moisture Content and Specific Gravity

After the bending failure test of the GLT, moisture content specimen (20×20×20 mm) and specific gravity specimen (20×20×30 mm) were collected from a clear area close to the failure part. The moisture content and specific gravity was measured according to the KS F 2199 and KS F 2198, respectively. The moisture content and ovendry specific gravity of the control GLT was 8.24±0.33% and 0.43 ± 0.06%, the top chord GLT of A type was 7.55±0.57% and 0.46 ± 0.06%, B type was 7.82±0.71% and 0.48 ± 0.04%, respectively.

Fabrication of Hybrid Inverted King-post Timber Truss

Two types of hybrid inverted king-post timber truss were manufactured with different height of the central vertical web (A (15 cm) and B (30 cm), Fig. 2). The hardware for vertical web materials is SS275 (diameter 60 mm, thickness 4 mm), turnbuckle is SS275 (diameter 12.7 mm) and STS304 (diameter 15.875 mm), tensile bar is SS275 (diameter 12 mm) and STS304 (diameter 16 mm), and side plate is SS275 (width 140 mm, thickness 6 mm, height 75 mm), respectively.

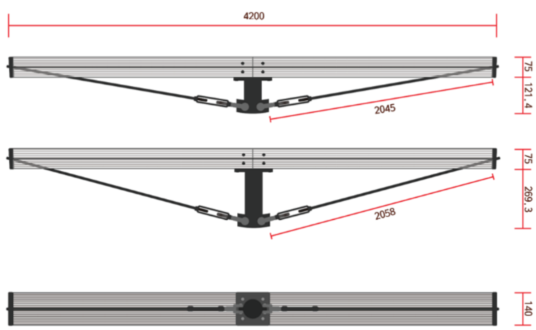

Figure 2. Configuration of hybrid inverted king-post timber truss

Table 3: Hardware specifications

Material	*Before reinforcement*	*After Reinforcement*	*Standard*
Vertical web member	SS275	-	KS D 3503 (General structural rolled steel)
Side Hardware			
Tension bars		STS304	KS D 3706 (㉿Stainless steel bar)
Turnbuckle			

Table 4: Mechanical properties of SS275 and STS304

Sample	*Thickness of steel (mm)*	*Yield strength (N/mm2)*	*Tensile strength (N/mm2)*	*Elongation (%)*
SS275	Under 15	Over 275	Between 410 and 550	Over 18
STS304	-	Over 205	Over 520	Over 40

Specimen Design

The test specimens consisted of 5 A-type and B-type inverted king-post timber trusses, and 5 GLT specimens as a control group. The specifications of each specimen are shown in Table 5. The connection part of the hybrid inverted king-post timber truss was shown in Fig. 3.

Table 5: Specification of hybrid inverted king-post timber truss

Class	*No. of specimen*		*Thickness of Tension bar (mm)*	*Turnbuckle dimensions (mm)*	*Connection bolt (mm)**
A (15)	1	a	12	12.700	M10
		b	12	12.700	M10
	2	a	16	15.875	M10
	3	a	16	15.875	M12
		b	16	15.875	M12
B (30)	1	a	12	12.700	M10
	3	a	16	15.875	M12
		b	16	15.875	M12
		c	16	15.875	M12
		d	16	15.875	M12

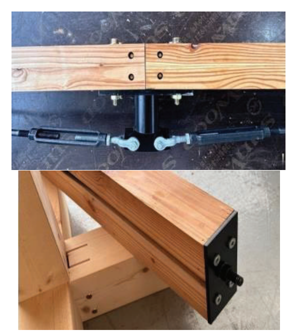

Figure 3. Hardware for hybrid inverted king-post timber truss

2.3 BENDING TEST

The bending test was conducted using RB 301 Unitech-M (R&B Co., Korea) for the three-point bending test of KS F 3021 (Fig. 4). The span was adjusted to more than 3600 mm so that the lower tension bar of each test piece did not interfere with the load support point. The load speed was 10 mm/min until failure. The displacement was limited to 300 mm. The modulus of rupture (MOR) and the modulus of elasticity (MOE) were calculated by the following equations (1) and (2). The cross section for calculating MOR and MOE of the hybrid inverted king-post timber truss was the cross-sectional area of the control GLT to facilitate comparison with the control group.

$$MOR\left(\frac{N}{mm^2}\right) = \frac{3P_mL}{2bh^2} \quad (1)$$

$$MOE\,(N/mm^2) = \frac{P_eL^3}{4\Delta_e bh^3} \quad (2)$$

https://doi.org/10.52202/080513-0525

where, P_m: maximum load (N), L : span length (mm), b : width (mm), h : thickness (mm), P_e : load at proportional limit (N), Δ_e : displacement at proportional limit (mm)

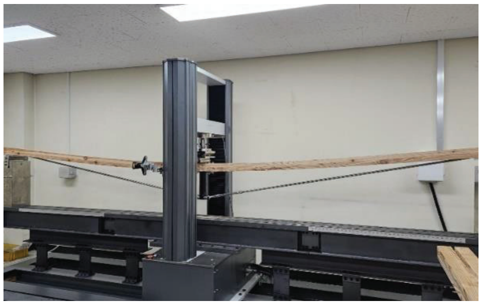

Figure 4. Bending test of the specimen

3 – RESULTS AND DISCUSSIONS

3.1 BENDING TEST

MOE and MOR

The MOE and MOR of the tested specimens are shown in Table 6. The maximum load of the GLT was 21.29±4.07 kN, the MOE was 10.38 ±0.48 GPa, and the MOR was 36.49±6.99 MPa. In the case of A-1, in which failure occurred in the thread of tension bar connection, the average MOE was 3.47 GPa, and the average MOR were 21.23 MPa, and the MOE and MOR was 33.43% and 58.18% of the control GLT, respectively. The A-1 specimen under the bending load was failed in tension of the bottom chord connection. The tensile performance of the tension bar was designed not enough to support the tensile stress on the bottom chord. Therefore, in order to improve the tensile strength of the bottom chord, the diameter of the tension bar was increased from 12 mm to 16 mm, and the turnbuckle was increased from 12.700 mm to 15.875 mm (A-2). As a result, A-2 had MOE of 3.72 GPa and MOR was 21.07 MPa, respectively. It was 35.84 % (MOE) and 57.74% (MOR) of control GLT. In the case of A-2, tensile plastic deformation was observed in the turnbuckle. Therefore, the property of connecting hardware was improved from M10 to M12 to produce an A-3 specimen. The A-3 had MOE of 4.1 GPa and MOR of 25.28 MPa, which were 40% (MOE) and 69% (MOR) of the control GLT. The tensile strength of the bottom chord tension bar was improved to increase the bending performance of the hybrid inverted king-post timber truss. In the case of the length of the vertical web was short (15 cm), the tensile load acting on the bottom chord tension bar was very large, so it was not easy to improve the flexural performance of the hybrid truss by improving the diameter and material.

To reduce the tensile load on the bottom chord of the hybrid truss system, the length of vertical web was increased to 30 cm (B type). In the case of B-1, in which the material of the tension bar and the connecting hardware is the same as A-1, the MOE was 11.20 GPa (108% of GLT) and the MOR was 34.98 MPa (96% of GLT). The bending load resistance of the hybrid truss increased by decreasing tensile stress applied to the bottom chord. The tensile stress of the bottom chord can be decreased by extending the length of the vertical web material. Also, the increasing tensile strength of the bottom chord is the other method to reinforce bending performance of truss system. Therefore, the experiment was conducted by increasing the diameter of the tension bar from 12 mm to 16 mm, the turnbuckle from 12.700 mm to 15.875 mm, and the connecting hardware from M10 to M12 (B-3). Compared to the control GLT, the B-3 showed that average MOR was 52.97 MPa (145% of GLT) and an average MOE was 12.83 GPa (124% of GLT).

Table 6: Bending properties of hybrid inverted king-post timber truss

Sample	*Average Maximum load (kN)*	*MOE (GPa)*	*Average*	*MOR (MPa)*	*Average*
GLT 1	21.29 ±4.07	10.41	10.38 ±0.48	28.36	36.49 ±6.99
GLT 2		9.73		39.66	
GLT 3		10.72		29.69	
GLT 4		10.93		40.98	
GLT 5		10.09		43.75	
A-1-a	12.39 ±2.04	3.21	3.47 ±0.36	18.76	21.23 ±3.50
A-1-b		3.72		23.71	
A-2-a	12.29	3.72	3.72	21.07	21.07
A-3-a	14.03 ±0.40	4.83	4.10 ±1.04	26.99	25.28 ±2.41
A-3-b		3.36		23.57	
B-1-a	18.84	11.20	11.20	34.98	34.98
B-3-a	28.09 ±2.26	13.13	12.83 ±0.39	57.72	52.97 ±4.26
B-3-b		12.27		48.47	
B-3-c		12.88		55.24	
B-3-d		13.03		50.44	

Failure mode

The load-displacement curve of the bending test was shown in Fig. 5. The GLT as control showed linear and brittle failure. All GLT specimens were observed to be tension failure in the outermost tensile layer.

In the case of A-1 and B-1, tensile plastic deformation and failure was occurred in the connection thread of the bottom chord tension bar (Fig. 6). In the case of the hybrid inverted king-post timber truss, a ductility was maintained after reaching the yield load. The tension bar was elongated after the yield load and it was considered as the plastic behavior of the truss system (Mei, L et al., 2021). In A-2-a, bending failure of the turnbuckle bolt occurred (Fig.7), and the longitudinal elongation of the turn buckle body was about 0.7 cm for A-3 and 1.5 cm for B-3. (Fig.7)

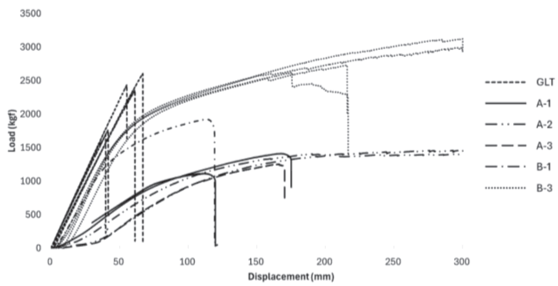

Figure 5. Load-displacement curve of bending test

Figure 6. Tensile plastic deformation and failure of tension bar

Figure 7. Deformation of hardwares (left : A-2-a, right : B-3, A-3)

3.2 STRESS ANALYSIS OF THE HYBRID INVERTED KING-POST TIMBER TRUSS

In the case of hybrid truss, the method of improving bending performance is to distribute the size of bending stress evenly to each member or to use high strength and rigidity of member where bending stress is concentrated.

Plastic behavior was observed after the yield strength of the hybrid inverted king-post timber truss due to the steel tension bar as bottom chord. The top chord is under the compressive stress which is GLT in this study. In particular, the compressive stress is applied to the parallel to the grain direction of GLT. The GLT top chord can support compression load up to its compressive strength if there is no buckling. Therefore, the ductile deformation by the bending load of the hybrid inverted king-post timber truss occurred by the tensile behavior of the steel bottom chord.

In this study, the tension bar materials were SS275 of carbon steel and STS304 of alloy steel, respectively (Table 4). If the tensile yield strength of the tension bar was exceeded, permanent deformation occurs due to plastic behavior of the material. After the tensile proportional limit, the steel material showed plastic tensile deformation, resulting in ductile behavior in the hybrid truss (Mei et al., 2021; Kim et al., 2006). Since the turnbuckle, the tension bar, and the turnbuckle fixing bolt are in the same tensile system, they received the same tensile force. In order to calculate the tensile force acting on the tension bar, the member force of each truss element was examined through equations (3) and (4). The load on the vertical web material was analyzed by applying the load generated in the ductile behavior of the hybrid truss.

$$T = \frac{P}{2Sin\theta} \qquad (3)$$

$$\sigma_T = \frac{T}{A} \qquad (4)$$

Where, T : tensile force of the tension bar (N), P : initial load of plastic behavior (non-linear section) (N), θ : angle between the horizontal member and the tension bar (°), σ_T : Tensile stress acting on the tension bar (MPa), A : Cross-sectional area of the tension bar (mm2)

Table 7 shows the analysis results of the tensile load acting on the tension bar of the hybrid inverted king-post timber truss. The vertical load (P) was calculated as the load at the initial load of plastic deformation of the hybrid truss in the bending experiment, and the tensile load applied to the tension bar at the corresponding load was calculated.

As a result of examining the tensile force acting on the tension bar under the conditions A-1 and B-1 with a diameter of 12 mm of the SS275 material, failure or plastic deformation was generally predicted at low loads. At about 7.56 kN of bending load, the tensile stress of the tension bar was 443.20 MPa, exceeding the tensile strength of SS275 (about 410 MPa), and in the experiment, it was fractured in the thread of the tensile bar connection part. At about 5.30 kN of begining load, the tensile stress of A-1-b was 310.62 MPa, exceeding the yield strength of SS275 (about 275 MPa). In the case of B-1, plastic deformation was predicted by exceeding the yield strength with a tensile stress of 279.02 MPa at a bending load of 9.12 kN, but in the actual experiment, destruction occurred in the thread of the connection part of the tension bar. This is considered to be the result of the concentration of local stress because SS275 has lower yield strength, tensile strength, and elongation rate than STS304 and is small diameter of the tension bar by thread processing.

On the other hand, in the case of A-2, A-3 and B-3 which were improved to STS304 and 16 mm in diameter, the elastic and plastic deformation were predicted under high bending loads. A-2 and A-3-b had a bending load of 4.46 kN and 5.58 kN, respectively, and the tensile stress was

 https://doi.org/10.52202/080513-0525

calculated to be about 147.10 MPa and 183.94 MPa, and the tensile strength of STS304 was not exceeded (about 205 MPa), so the elastic behavior was performed. B-3-a and B-3-b had the maximum bending load resistance of 14.57 kN and 13.53 kN, respectively. Under the condition, the tensile stress of the tension bar was applied to 250.69 MPa and 232.85 MPa, and plastic deformation was predicted to exceed the yield strength. In the case of B-3-c and B-3-d, the maximum bending load resistance were 9.40 kN and 10.96 kN, respectively, which were 161.67 MPa and 188.54 MPa of tensile stress of bottom chord, respectively, so the elastic behavior was predicted as they did not exceed the yield strength (about 205 MPa) of STS304. This was judged to be the result of an increase in load distribution capacity and rigidity as the tensile strength of STS304 was high and the cross-sectional area of the tensile bar became relatively large.

Table 7: Tensile stress acting on the tension bar

	P (kN)	*T (kN)*	*D (mm)*	*σ_T (MPa)*	*Steel*	*Behavior*
A-1-a	7.56	50.13	12	443.20	SS275	fail
A-1-b	5.30	35.13	12	310.62	SS275	PD
A-2-a	4.46	29.57	16	147.10	STS304	ED
A-3-a	6.27	41.53	16	206.54	STS304	PD
A-3-b	5.58	36.98	16	183.94	STS304	ED
B-1-a	9.12	31.56	12	279.02	SS275	PD
B-3-a	14.57	50.40	16	250.69	STS304	PD
B-3-b	13.53	46.82	16	232.85	STS304	PD
B-3-c	9.40	32.50	16	161.67	STS304	ED
B-3-d	10.96	37.91	16	188.54	STS304	ED

D: Tension bar diameter, σ_T : Tensile stress acting on the tension bar, PD : Plastic Deformation, ED : Elastic Deformation

The length of the vertical web material of the hybrid inverted king-post timber truss affects the load distribution acting on the bottom chord, tension bar. Failure or plastic deformation was predicted at A, which is 15 cm in length of the vertical web material, but elastic or plastic deformation was predicted even at a high load at B, which is 30 cm. In particular, the maximum load was the highest at 14.57 kN in B-3, showing the greatest bending performance. As the height of the vertical web increased, the size of the load applied to the tension bar decreased, and the load support capacity of the hybrid inverted king-post timber truss was improved to ensure rigidity and structural safety.

In order to maximize the bending performance of the hybrid inverted king-post timber truss, it was suggested that i) the height of the vertical web member was increased, ii) design the members and truss system to distribute stress evenly for the members.

4 – CONCLUSION

This study was conducted to analyze the bending performance and behavior of the hybrid inverted king-post timber truss and the following conclusions were drawn.

With the half of the cross-sectional area of GLT, the hybrid inverted king-post timber truss showed the possibility of greater bending performance than the GLT.

The hybrid inverted king-post timber truss with stronger material and greater diameter of the tension bar (B3) showed the highest bending performance, confirming its applicability as a structural material. To reduce the wood resources and to elongate span length of the bending member, the hybrid with timber and steel truss system can be the solution.

The method of maximizing the performance of the hybrid inverted king-post timber truss is designing the system to properly distribute the load acting on the entire structure to each member, and each member to support the maximum load acting on the member. In particular, it is considered that the possibility of utilizing hybrid timber truss with GLT using domestic small and medium-sized wood resources was presented for large and high-rise timber constructions.

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