Experimental Study on the Lateral Resistance of Reinforced Glued-Laminated Timber Post and Beam Structures

Haibei Xiong¹, Yingyang Liu*², Ya Yao¹ and Bingyang Li³

¹Professor, College of Civil Engineering, Tongji University, China
²Ph.D., School of Civil Engineering, Zhengzhou University, China
³Engineer, Shanghai Institute of Mechanical and Electrical Engineering Co., Ltd., China
⁴Engineer, Henan Electric Power Survey and Design Institute, China

Abstract

Nine cyclic tests were conducted on full-scale one-story, one-bay timber post and beam construction specimens to study the lateral resistance of reinforced glued-laminated timber post and beam structures. Two reinforcement methods, wrapping fiber-reinforced polymer (FRP) and implanting self-tapping screws, and two structural systems, simple frame and knee-braced frame, were considered in the experimental tests. Based on the observed experimental phenomena and the test results, the feasibility of the reinforcement was discussed; the contributions of different methods were evaluated; and the seismic performance of the specimens were studied. The results indicated that both reinforcement methods could limit the crack development and improve the strength, stiffness and energy dissipation capacity. The results also showed that the lateral resistance could be significantly improved by retrofitting a failed simple frame with joint reinforcement and a knee-brace, demonstrating that this approach can be applied in engineering practice.

Keywords: timber post and beam structure; reinforcement; FRP; self-tapping screw; cyclic test

1. Introduction

Glued-laminated timber (glulam) is an extensively used building material that provides stable performance and is one of the most commonly used materials in modern post and beam structures. The component members are typically connected with metal connectors, which are often bolted connections with slotted steel plates due to their simplicity. When subjected to lateral loading, semi-rigid bolted joint connections experience bending moments, resulting in tension perpendicular to the wood grain and longitudinal shear stress (the two weakest strength properties of timber). This often leads to premature splitting at the joints and damage to the bolted timber frame under lateral loading. Therefore, the reinforcement for bolted timber post and beam structures should be studied and understood in detail.

The research on this topic has primarily focused on two reinforcement approaches: using fiber-reinforced polymer (FRP) and using self-tapping screws. Yang and Liu (2007), Yang et al. (2008), Shao and Liu (2012) conducted experimental studies on the behavior of glulam beams and columns and compared the results of regular beams and FRP-reinforced beams; the test results showed that the reinforcement improved the stiffness, the load bearing capacity, and especially the ductility. Li et al. (2013) conducted experiments on FRP columns to investigate the effects of different wrapping methods. The columns were wrapped using toroidal, single-helix, double-helix and cross-helix methods and were tested via axial compressive loading. Echavarría et al. (2014) investigated the mechanical performance of glulam beams reinforced with bamboo, punched metal plates, glass fiber-reinforced polymer (GFRP), or carbon fiber-reinforced polymer (CFRP). The results showed that the behavior of the reinforced glulam beams is more uniform than that of the unreinforced beams and that the reinforced beams were less sensitive to weak sections when loaded to failure.

Echavarría (2007) carried out studies using self-tapping screws with continuous threads in the joint area as reinforcement to avoid the splitting of timber members. The reinforced specimens exhibited a less catastrophic failure mode, whereas the non-reinforced specimens failed in a brittle manner; in addition, the reinforced specimens showed greater embedding and ultimate strength. Lam et al. (2010) conducted experimental studies on the moment resistance of...
bolted timber connections. A total of 30 connection tests were performed on specimens with regular connections, with connections reinforced with self-tapping screws and with failed regular connections retrofitted with self-tapping screws. These tests sought to investigate whether long self-tapping wood screws improve the performance of bolted timber connections subjected to a moment load. The test results showed that the reinforced and retrofitted connections increased capacity by 1.70- and 1.53-fold, respectively, compared with the regular connections under reverse cyclic loading. Kasal et al. (2014) reinforced beam-to-column connections using self-tapping screws and used hardwood blocks to support the beams. The moment-rotation characteristics of the connections were measured by applying static cyclic loads, and highly linear behavior was observed. Yeh et al. (2014) conducted experimental tests to study the characteristic strength properties of structural glulam connections assembled with self-tapping screws. Varying numbers of four screw types were designated at each connection of the beam-girder structure with different nailing schedules. The results indicated the following: the load bearing capacity and dissipated energy increased as the screw diameter increased; the initial stiffness improved with an increasing number of screws; and screws with both double-threaded sections and fully threaded shanks increased the stiffness more than single-threaded screws. Furthermore, Angst and Malo (2012) studied the effect of self-tapping screws on moisture-induced stress in the glulam component; their test results indicated that the screws improved the low tensile strength of glulam perpendicular to the grain.

The above research results demonstrate that timber performance, especially in the perpendicular-to-grain direction, can be efficiently improved by using FRP and self-tapping screws as reinforcement. However, the existing research has mainly focused on the components and joint connections, with few studies conducted at the structural level. In this paper, nine cyclic tests were performed on full-scale one-story, one-bay timber post and beam construction specimens, considering both reinforcement methods. The main objectives of this study were as follows: 1) discuss the feasibility of the reinforcement, 2) evaluate the contributions of different methods and 3) study the seismic performance of the specimens.

2. Test Program
2.1 Materials

The following materials were used in this experimental study:

Canadian spruce-pine-fir (SPF) glulam was used to fabricate the columns, beams and braces for the post and beam frames. Bolts with a grade of 8.8 (equivalent to ASTM A325 bolts), conforming to Chinese Standard GB/T1231-2006 (China Machinery Industry, 2006), were used as the specimen fasteners. The maximum tensile strength and yield point of the bolts were 800 and 640 MPa, respectively. Mild carbon steel Q235B with a thickness of 10 mm, conforming to Chinese Standard GB 50017-2003 (China Ministry of Construction, 2003), was used as the steel plates for the connections. The yield point of the steel plates was 235 MPa.

Würth ASSY plus VG self-tapping wood screws with continuous threads were used to reinforce the joint connections. The screws were 280 mm long and 8 mm in diameter. The characteristic value of the screws' yield moment was 20 Nm, and the maximum tensile capacity was 20 kN. The joint area was wrapped with 0.11-mm-thick CFRP. The tensile modulus of elasticity was 244 GPa, and the maximum tensile strength was 3,910 MPa.

2.2 Specimen Design

Nine full-scale one-story, one-bay timber post and beam construction specimens were designed for the experimental study. All of the specimens had a span of 4,110 mm and a height of 2,740 mm (span-depth ratio of 1.5). The column sections were 280 mm x 230 mm; the beam sections were 280 mm x 180 mm; and the brace sections were 135 mm x 105 mm. The joint connections were bolted glulam connections slotted in steel plates. Other details of the configuration can be found in Xiong and Liu (2014). The moisture content of the specimens ranged from 12% to 14% during the tests.

To investigate lateral performance improvements, three unreinforced regular specimens were tested as the "U" series, and six failed frames [cracks at the end of the column and beam (Xiong and Liu, 2014)] reinforced with FRP ("FR" series) or self-tapping screws ("SR" series) were then tested as the "R" series. The reinforcement configuration is shown in Fig.1. Two structural systems were considered: simple frames ("F" series) and knee-braced frames ("HB" series).
2.3 Test Setup and Instrumentation

Monotonic and cyclic tests were performed using a hydraulic actuator (Schenker hydraulic loading system manufactured by American MTS Systems Corporation) at Tongji University. The hydraulic actuator had a displacement range of ±250 mm and a capacity of 650 kN. The actuator was secured between the concrete reaction wall and steel plate at the elevation corresponding to the top of the column. A hinge was placed between the hydraulic actuator and steel plate to eliminate the bending moment generated by the gravity of the actuator, thus applying the horizontal reverse load in a simpler manner. The pulling load was transferred by the steel tie bar to avoid the partial failure of the left beam-column joint. For the boundary conditions, the bottoms of the columns were fixed to the ground beam with eight bolts (22 mm diameter). In addition, out-of-plane stability was ensured via a steel roller installed on the gantries. The test setup is shown in Fig.2.

The following test observations (Fig.3.) were recorded: 1) loading force (exported directly from the hydraulic loading system), 2) horizontal displacement at the top of the column, 3) relative rotation of the joint (measured using coupled displacement sensors), 4) diagonal elongation of the frame, 5) pulling up of the column, and 6) base slip.

2.4 Test Procedure

According to the American Society for Testing and Materials (ASTM) E2126 (ASTM, 2012b) and the test methods used by other scholars (Kohara, 2006; Komatsu et al., 2006; and Noguchi et al., 2006), the horizontal reversed load was applied using a displacement control method without a vertical load on the columns or beams. The procedure is shown in Fig.4.

The first displacement pattern consists of five single fully reversed cycles at displacements of 1.25%, 2.5%, 5%, 7.5%, and 10% of the ultimate displacement \( \Delta_{m} \). The second displacement pattern consists of phases, each containing three fully reversed cycles of equal amplitude at displacements of 20%, 40%, 60%, 80%, 100%, and 120% of the ultimate displacement \( \Delta_{m} \).

The ultimate displacement \( \Delta_{u} \) was obtained from the corresponding specimens in the monotonic tests (Xiong and Liu, 2014) based on ASTM E564 (ASTM, 2012a). For the simple frame, \( \Delta_{u,F} = 250 \text{ mm} \); for the knee-braced frame, \( \Delta_{u,HB} = 40 \text{ mm} \).

The test was terminated either when the load decreased to 80% of the ultimate load or when the lateral displacement reached 250 mm.

3. Experimental Phenomenon and Failure Mode
3.1 Simple Frame of the U Series

The joints were examined for local pressing as the lateral displacement increased. Because the tension was perpendicular to the wood grain, longitudinal shear stresses appeared, and cracks developed in the timber members. The bottom of the columns first split when the lateral displacement reached 50 mm (drift ratio of 1.8%); cleavage cracks then occurred at the end of the beams at a lateral displacement of approximately 100 mm (drift ratio of 3.6%). The cleavage cracks (Fig.5.) continued to develop during the subsequent loading process without a significant reduction in load. The test was terminated when the lateral displacement reached 250 mm (drift ratio of 9.1%).

The failure mode of the simple frame indicated that the joints were weak but the members were strong. When the simple frame was subjected to lateral loading, the semi-rigid joint connections experienced bending moments, which created tension perpendicular...
to the wood grain and a longitudinal shear stress (the two weakest strength properties of timber), which likely caused the premature splitting at the joints. Thus, the simple frame with wood-steel-wood bolted joint connections was easily damaged under lateral loading.

3.2 Simple Frame of the R Series

During the test of the simple frame specimen reinforced with FRP, some cured adhesive on the surface of the column was stripped in the early loading process, and sounds were heard. When the lateral displacement reached 50 mm (drift ratio of 1.8%), some cracks occurred at the bottom of the columns; however, unlike the U series specimens, the wrapped FRP was able to limit the splitting to within the first reinforcement layer. With increasing displacement, some crushing was found at the end of the beams, and splitting was still restrained by the first FRP layer. When the test was terminated at the lateral displacement of 250 mm (drift ratio of 9.1%), the joint connections remained mostly intact, with only some crushing in the component pressing area (Fig.6.).

For the specimen reinforced with self-tapping screws, the timber splitting control effect at the joint connection was slightly weaker than that of the FR series. Cleavage cracks developed between the first and second reinforcement layers (Fig.7.).

Both reinforcement methods performed well in controlling the crack development at the joint connection, improved the weak-joint failure mode of the simple frame structural system, and increased the load bearing capacity of the simple frame structure.

3.3 Knee-braced Frame of the U Series

No significant failure was observed in the early loading process of the knee-braced frame; however, sounds were detected near the wood and bolt contact areas. As the lateral displacement increased, cleavage cracks appeared at the bottom of the columns, whereas the beam-to-column joint connections were preserved by the knee-braces. The test ended as the load decreased rapidly at a lateral displacement of 150 mm (drift ratio of 5.5%), when the brace components failed; this failure was caused by the buckling of the slotted steel plate, the splitting of the brace element, and the bending yield failure of the bolts in the braces (Fig.8).

3.4 Knee-braced Frame of the R Series

The wood splitting that occurred at the bottom of the columns for the specimens of the U series was controlled by the reinforcement. The effect of the reinforcement was very similar to that of the reinforced simple-frame specimen group. The failure of the knee-braced frame structural system was governed by the brace component members. Hence, the failure modes of the R series knee-braced frame specimens were similar to those of the U series; only a few differences in the load bearing capacity and ultimate failure displacement were recorded.

4. Experimental Results and Analysis

4.1 Mechanical Performance Parameters

Fig.9. shows the hysteresis curves that reflect the overall seismic performance of the structures as well as the envelope curves. Fig.10. shows the envelope curves of all the specimens. The peak load \( P_{\text{peak}} \), displacement corresponding to \( P_{\text{peak}} \) \( \Delta_{\text{peak}} \), failure load \( P_u \), and ultimate displacement \( \Delta_u \) can be determined from the average envelope curve. The yield point is determined using the equivalent energy elastic-plastic (EEP) curve (Fig.11.). The mechanical performance parameters of the specimens are listed in Table 1.

All of the hysteresis curves exhibited a pinched mode due to the bolt-connected joint type. The bolt compressed one side of the wood when a load was applied; then, a gap formed between the bolt and the other side of the wood due to the absence of tensile stresses at the bolt-wood interface. Thus, the unloading stiffness was extremely low. When the wood experienced plastic deformation, the reloading stiffness under the previous displacement amplitude also decreased rapidly. These two behaviors caused the pinching of the hysteresis loops.

For the simple frame specimens, the U series had a load bearing capacity of 55.0 kN and an elastic stiffness of 0.35 kN/mm. The FR series and SR series both showed an ability to recover the load bearing
capacity; they increased the capacity by 10% and 25%, respectively. The SR series showed the greatest improvement in the elastic stiffness (1.14-fold increase compared to the U series specimen) due to the pretensioning effect of the self-tapping screws, which increased the stiffness of the joint connection; the FR series tended to passively limit the cracks and thus showed a smaller elastic stiffness (71% of that of the U series specimen).

For the knee-braced frame specimens, the lateral resistance capacity was mainly determined by the brace component. As a result, the load bearing capacity and lateral stiffness were similar for the U series and R series.

The knee-braced frame provided greater load bearing capacity and lateral stiffness than the simple frame. For the U series, the load bearing capacity and lateral stiffness of the knee-braced frame were 2.4 and 2.5 times higher compared to those of the simple frame.

The R series specimen was able to effectively recover the lateral performance of the failed U series specimen, and the knee-braced frame significantly improved the lateral resistance compared with the simple frame. Thus, failed post-and-beam frames can be retrofitted by reinforcing the joint and then adding knee-brace members in engineering practice.

### 4.2 Lateral Stiffness

The lateral stiffness under reversed cyclic loading is determined using the secant stiffness (China Academy of Building Research, 1996):

![Hysteresis Curves](image1)

![Envelope Curves](image2)

![Fig.9. Hysteresis Curves](image3)

![Fig.10. Envelope Curves](image4)

| Specimen | $P_{\text{peak}}$ (kN) | $\Delta_{\text{peak}}$ (mm) | $P_u$ (kN) | $\Delta_u$ (mm) | $P_{\text{yield}}$ (kN) | $\Delta_{\text{yield}}$ (mm) | $K_e$ (kN/mm) |
|----------|------------------------|----------------------------|-------------|-----------------|------------------------|--------------------------|---------------|
| F1       | 54.5                   | 204.7                      | 53.1        | 260.0           | 52.8                   | 155.0                    | 0.34           |
| F2       | 55.5                   | 207.5                      | 55.3        | 258.9           | 53.7                   | 154.1                    | 0.35           |
| FRF1     | 60.3                   | 243.8                      | 60.3        | 243.9           | 51.2                   | 202.8                    | 0.25           |
| SRF1     | 69.0                   | 241.9                      | 69.0        | 241.9           | 62.9                   | 156.2                    | 0.40           |
| HB1      | 130.7                  | 134.9                      | 104.6       | 155.6           | 128.0                  | 145.6                    | 0.88           |
| FRHB1    | 121.7                  | 161.7                      | 97.4        | 176.4           | 121.7                  | 161.7                    | 0.75           |
| FRHB2    | 124.0                  | 164.7                      | 99.1        | 177.2           | 123.9                  | 164.7                    | 0.75           |
| SRHB1    | 118.2                  | 162.5                      | 94.6        | 181.0           | 118.2                  | 162.5                    | 0.73           |
| SRHB2    | 115.5                  | 167.1                      | 92.4        | 191.9           | 115.5                  | 167.1                    | 0.69           |

Note: the mechanical performance parameters represent the average value of the specimens of one structure type.
where $F_i^+$ ($F_i^-$) is the peak load of each cycle and $X_i^+$ ($X_i^-$) is the relative displacement.

\[
k_i = \frac{F_i^+}{X_i^+} = \frac{F_i^-}{X_i^-}
\]

(1)

Fig. 11 shows the secant stiffness curves of the specimens.

The FR series showed the highest initial stiffness (1.03 kN/mm, 3.00-fold increase compared to the U series specimen) of the simple frame specimens because some adhesive seeped into the bolt holes when gluing the FRP onto the joint area. Some bolts were connected with wood, thus providing initial strength to the joint connection. With increasing lateral load, the adhesive between the bolt and wood was stripped, which significantly decreased the lateral stiffness of the FR series. In the later stages of the loading process, the SR series performed better than the FR series and U series, which is in agreement with the previous analysis that the self-tapping screws performed in an active manner.

For the knee-braced frame specimens, the lateral stiffness was mainly provided by the brace component. In the initial linear stage, the stiffness values varied slightly due to the assembly differences of the brace members. In the later stages of the loading process, the specimens in the same series showed similar stiffness values, and the U series showed a higher value than the R series (take the 31st cycle as an example, 0.94 kN/mm for the U series, 0.68 kN/mm for the FR series and 0.65 kN/mm for the SR series). At the later stages (i.e., after the failure of the brace members), all of the specimens had low lateral stiffness values that were approximately the same as those of the simple frame specimens.

4.3 Energy Dissipation

Energy dissipation is an important indicator for measuring the structural seismic performance of a structure and can be determined from the area of the hysteresis curve. Fig. 12 shows the energy consumption of the specimens within each cycle group and the overall energy dissipation.

The energy dissipation of the timber frame structure occurred primarily through the yielding of the bolts, the friction between the components and the splitting of the wood. At larger lateral displacements, the wood components tended to split, thereby releasing high amounts of elastic strain energy and providing some of the structural energy dissipation. At the same displacement amplitude, the first cycle showed the best energy dissipation characteristics because few new cracks formed in the later cycles.

The wood members at the joint area were strengthened by the reinforcement; as a result, the steel bolts could yield to a greater degree. For the simple frame specimens, the R series showed a greater energy dissipation capacity than the U series; when the lateral displacement reached 9633 mm at the 20th cycle, the cumulative energy dissipation of the U series, FR series and SR series were 31.01 kJ, 49.31 kJ (1.59-fold increase compared to the U series specimen) and 52.97 kJ (1.71-fold increase compared to the U series specimen), respectively. The knee-braced frame specimens showed a similar energy dissipation.
characteristic before the failure of the brace members, as the main energy dissipation was provided by the yielding of the bolts in the braces. After the brace members failed, the energy dissipation shifted to the frame joint connection; subsequently, the knee-braced frame specimens exhibited a similar energy dissipation capacity as that of the simple frame specimens.

5. Conclusions

This paper presented an experimental study of nine full-scale one-story, one-bay bolted timber post and beam construction specimens considering two reinforcement methods, wrapping FRP and implanting self-tapping screws, and two structural systems, simple and knee-braced frames. The feasibility of the reinforcement methods, the contributions of different methods and the seismic performance of the specimens were studied. The following conclusions can be drawn from the observations of the experimental phenomena and the analyses of the results:

1. Both of the studied reinforcement methods performed well in improving the weak-joint failure mode. The FR series joint remained mostly intact, with only a small amount of crushed material at the bottom of the column and at the end of the beam. The SR series limited the cracks remain within the second reinforcement layer.

2. All of the specimens of the R series were shown to recover the load bearing capacity. The implanted self-tapping screw provided a pre-tensioning effect, whereas the wrapped FRP tended to limit the cracks passively.

3. In practical engineering work, a failed simple frame can be retrofitted by reinforcing the joint and adding a knee-brace to improve the lateral resistance.

4. The wood members at the joint area were strengthened by the reinforcement, thus enabling the steel bolts to yield to a greater extent. As a result, the R series specimens showed a better energy dissipation capacity than the U series specimens.

References

1) Angst, V. and Malo, K. (2012) Effect of self-tapping screws on moisture induced stresses in glulam. Engineering Structures, 45, pp.299-306.
2) ASTM. (2012a) Standard practice for static load test for shear resistance of framed walls for buildings. E564-06, West Conshohocken, PA: ASTM International.
3) ASTM. (2012b) Standard test methods for cyclic (reversed) load test for shear resistance of vertical elements of the lateral force resisting systems for buildings. ASTM E2126-11. West Conshohocken, PA: ASTM International.
4) China Academy of Building Research. (1996) Specification of test methods for earthquake resistant building. JGJ101-96. Beijing: China Architecture and Building Press.
5) China Machinery Industry. (2006) Specifications of high strength bolts with large hexagon head, large hexagon nuts, plain washers for steel structures. GB/T1231-2006. Beijing: China Architecture and Building Press.
6) China Ministry of Construction. (2003) Code for design of steel structures. GB 50017-2003. Beijing: China Architecture and Building Press.
7) Echavarria, C. (2007). Bolted timber joints with self-tapping screws. Revista EIA, (8), pp.37-47.
8) Echavarria, C., Echavarria, B. and Cañola, H. (2014) Bamboo reinforced glulam beams: an alternative to punched metal plate, GFRP and CFRP reinforced glulam beams. Proc., 2014 World Conf. on Timber Engineering, FP Innovations, QC, Canada.
9) Xiong, H. and Liu, Y. (2014) Experimental study of the lateral resistance of bolted glulam timber post and beam structural systems. Journal of Structural Engineering, 142 (4), E4014002. DOI 10.1061/(ASCE)ST.1943-541X.0001205, E4014002.
10) Kasal, B., Guindos, P., Polocozer, T., Heiduschke, A., Urushadze, S. and Pospelus, S. (2014) Heavy laminated timber frames with rigid three-dimensional beam-to-column connections. Journal of Performance of Constructed Facilities, 28 (6), A4014014. DOI 10.1061/(ASCE)CF.1943-5509.0001594, A4014014.
11) Kohara, K. (2006) A study on experimental and structural design for timber rigid frame. Proc., 2006 World Conf. on Timber Engineering, Oregon State Univ. Conference Services, Corvallis, OR, pp.295-302.
12) Komatsu, K., Hosokawa, K. and Hattori, S. (2006) Development of ductile and high-strength semi-rigid portal frame composed of mixed species glulams and h-shaped steel gusset joints. Proc., 2006 World Conf. on Timber Engineering, Oregon State Univ. Conference Services, Corvallis, OR, pp.303-310.
13) Lam, F., Gehloff, M. and Clossen, M. (2010) Moment-resisting bolted timber connections. Structures and Buildings, 163 (4), pp.267-274.
14) Li, L., Yuan, S., Dong, J. and Wang, Q. (2013) An experimental study on the axial compressive behavior of timber columns strengthened by FRP sheets with different wrapping methods. 3rd International Conference on Civil Engineering, Architecture and Building Materials, Trans Tech Publications Ltd, Jinan, China.
15) Noguchi, M., Takino, S. and Komatsu, K. (2006) Development of wooden portal frame structures with improved columns. Proc., 2006 World Conf. on Timber Engineering, Oregon State Univ. Conference Services, Corvallis, OR, pp.311-318.
16) Shao J. and Liu W. (2007) Elastoplastic approach for studying the behavior of FRP confined wood column under axial compression. Journal of Building Materials, 10 (3), pp.282-287.
17) Shao, J., Xue, W., Liu, W., Jiang, J. and Jiang, T. (2012) Calculation of axial compressive behavior of timber column laterally strengthened with FRP. China Civil Engineering Journal, 45 (8), pp.48-54.
18) Yang, H. and Liu, W. (2007) Study on flexural behavior of FRP reinforced glulam beams. Journal of Building Structures, 28(1), pp.64-71.
19) Yang H., Liu W., Shao J. and Zhou H. (2008) Study on flexural behavior of timber beams strengthened with FRP. Journal of Building Materials, 11 (5), pp.591-597.
20) Yeh, M., Lin, Y. and Huang, G. (2014). Investigation of the structural performance of glulam beam connections using self-tapping screws. Journal of Wood Science, 60 (1), pp.39-48.