Research paper

# Investigation of the Structural Performance of Beam and Column Connections Using Hidden Threaded Rods[1)]

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## 【Summary】

A traditional wooden beam and column joint was revised using an embedded threaded rod with the assistance of dowels, and the structural performance of the joint in resisting the bending moment was examined in the study. Beam and column members of Japanese cedar and southern pine timber with a size of 120×120 mm were used to construct a T-structure which was then subjected to a cantilever load. The results indicated that the joint tightened with a threaded rod with 150 mm of embedded length in the side beam member showed a higher bending moment compared to those with 120- and 180-mm embedded lengths. The bending moment resistance of a joint in which a threaded rod was embedded at the upper location of the cross-section on the beam member was 4 times that at the lower location while exhibiting only 25.3% of the moment-rotation coefficient value. The bending moment capacity of joints tightened with a 60×60-mm washer was 40.2 and 36.2% higher than values of joints with 50×50-and 60×80-mm washers, respectively. The critical failure of a joint tightened with an embedded rod may have been due to the weak compressive strength perpendicular to the grain on the column member. When epoxy reinforcement was applied to the joint, the bending moment resistance of the Japanese cedar member joint with 2 embedded threaded rods improved 39.5%, and the internal rotation angle and moment-rotation coefficient were reduced by 21.6 and 40.6%, respectively. Overall, similar bending resistance values of beam and column joints assembled with both Japanese cedar and southern pine members were found after epoxy reinforcement was applied. The results also demonstrated a reduction of 68.4% in the moment-rotation coefficient for the joint with additional epoxy reinforcement.

**Key words:** joint, beam and column connection, Japanese cedar, bending moment resistance.

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研究報告

# 內藏式螺桿應用於梁與柱接合結構性能之探討[1)]

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## 摘　要

本研究採用以內藏式螺桿配合木釘作為傳統木材梁與柱之接合改良，並進行接合處之彎矩抵抗的結構性能分析。在試驗中採用斷面尺寸120×120 mm之柳杉及南方松作為梁與柱構材，並組成T字型結構進行懸臂之載重。結果顯示螺桿埋入梁端部深度150 mm之接合條件，較120及180 mm深度條件有較佳之彎矩抵抗。同時，螺桿埋入位置在梁構材斷面上方者，其彎矩抵抗為埋入梁斷面下方者之4倍，且彎矩旋轉係數僅為後者之25.3%。在梁接合處以60×60 mm尺寸之墊片緊固之條件下，其彎矩承載力分別較50×50-及60×80-mm尺寸墊片之接合條件高40.2及36.2%。以內藏螺桿接合之破壞關鍵多因柱構材材面之側向壓縮強度不足所致。在接合處以環氧樹脂補強方面，柳杉材以雙支螺桿接合者其彎矩抵抗可以改善39.5%，且內部旋轉角度及彎矩旋轉係數分別降低21.6及40.6%。整體而言，環氧樹脂補強處理後，柳杉及南方松之梁與柱構材接合均有相近彎矩抵抗性能，同時也顯示接合處之彎矩旋轉係數可以降低68.4%。

**關鍵詞**：接合、梁與柱連結、柳杉、彎矩抵抗。

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## INTRODUCTION

Wood-frame structures classified as light-framed buildings featured better seismic resistance. However, over 70% of the damaged historic buildings were wooden structures during the 921 Chi-Chi earthquake in 1999 in Taiwan (NCKU R&D Foundation 2000). Among these wooden structures, Chuan-dou wooden frame structures constituted 44% followed by Japanese post and beam frame (20%) and Dei-dou wooden frame structures (6%). Yeh et al. (2001) also reported 27% failure due to weak seismic resistance of post and beam structures in newly constructed wood-frame residential buildings which were damaged during the 921 Chi-Chi earthquake. The report also indicated that 62% of failures could be attributed to a lack of resistance to lateral forces by the main structures. These results revealed the importance of the structural performance of joints to resist lateral and vertical forces which is usually ignored when designing and constructing wood-frame buildings in Taiwan. Actually, a hinge or pin joint was assumed in wood-frame design practice based on the current code suggestion, which resulted in errors in the structural analysis due to neglecting any bending moment resistance of a joint (Chang and Hsu 2005).

The structural performance of traditional wood joints was recently examined. Chao (2004) suggested that failure always occurred at the joint between the column and beam for a traditional Dei-dou wood frame subjected to a vertical load. Beam members were detached from the mortises owing to the large displacement during simulated seismic loads. A reduction in 58% in the relative displacement at the column and beam joint could be achieved when a horizontal diaphragm was added to the roof system in the simulation. Lee et al. (2007) found that the maximum bending moment and rotational stiffness of a through tenon were 350 and 320%, respectively, higher than those of a straight tenon. And the stepped dovetail tenon also showed better bending moment resistance than did a straight tenon. However, the fit between the mortise and tenon of a traditional joint was set to 0 in the test, which is difficult to achieve at job sites. Chang et al. (2006) suggested the complexity of Taiwan Nuki joints is significant because of the gap between the column and beam compared to a similar joint used in Japanese traditional wood structures. They identified an initial slip behavior due to the rigid body motion and limited compression length in the early stage, and joints can be regarded as hinges. However, no significant relation was found between the 2 types of slip. To improve the structural performance of traditional wood joints, Hsieh (2005) suggested that high-strength stepped-dovetail connections be obtained by adding a wood wedge and 2 bamboo pegs, and adding 2 steel plates with 3 screws for Go-dou connections. On the other hand, no improvement in the joint strength of Go-dou connections was found when polyvinyl acetate glue was applied to the wedges before assembly.

Further, Harada et al. (2005) found that the maximum moment and stiffness of joints assembled with bolts and nails improved when wood members were dried with different moisture contents from green to 5%. But no clear effect of the moisture content on the joint strength was found for dovetail joints or mortise and tenon joints with precut processing. Pan et al. (2011) suggested that the tension strength perpendicular to the grain is an important property of a Korean traditional dovetail joint. The moment resistance of a joint increased as the cross-beam shoulder length and wood density increased. They pointed out that failure modes included split failure parallel to the grain at the post, rolling shear failure at the mortise branch, and split failure parallel to the grain at the beam shoulder.

To prevent a critical split or breaking failure of mortise and tenon joints and reduce the initial slip owing to an improper fit at the joint, a new connection between the column and beam members which can sustain a load through an adequate shearing capacity of the wood was proposed. Eckelman (1989) had a similar approach using through-bolt and dowel-type nuts in furniture rail member assembly and found the bending strength of a joint could be expressed as a relationship of the compressive strength parallel to the grain, the internal moment arm of the joint, and the end embedment distance of the dowel-type nut. Eckelman et al. (2007) further expanded this approach to construct a small timber truss with a through-bolt and cross pipe as heel connectors. They reported that the trusses did not fail catastrophically when the cross pipe began to yield, but continued to carry the load. In this study, a beam and column joint was designed to connect with a tension rod which was embedded inside the wood members and could be tightened with a nut and washer. The size of the washer and the embedded length of the threaded rod on the beam member which resulted in different shearing areas of the wood were considered. Also, the effect of the location and number of tension rods and reinforcement with epoxy adhesive application on the structural joint performance were examined.

## MATERIALS AND METHODS

### Material preparation

The 35~40-yr-old Japanese cedar (*Cryptomeria japonica*) plantation timber was harvested from the Hsinchu Forest District, Taiwan Forestry Bureau. Logs were then sawn, kiln-dried to a moisture content of 13%, and planed to 120×120×800 mm for column members and 120×180×1500 mm for beam members. Commercial southern pine timber (S) imported from North American was processed into the same dimensions with a moisture content of 15% and used for comparison in the study. “T”-shaped beam and column structures were assembled with bolts as shown in Figs. 1~3. The bolts had threads on both ends for 30 mm in length and were embedded inside both the column and beam members. Holes were first drilled from the cross-section of a beam end and in the middle of a column member. Notches were also made on the surface where bolt holes were located to accommodate washers and nuts for the assembly. A 52-mm-diameter wood dowel with a length of 100 mm was inserted into predrilled holes at the juncture of the joint to hold the beam member during assembly. The bolts were embedded in the beam to 3 different depths, i.e., 120, 150, and 180 mm from the end as shown in Table 1. The sizes of washers used on the beam members were 50 (length, l)×50 (width, w)×6 (thickness, t), 60 (l)×60 (w)×6 (t), and 60 (l)×80 (w)×9 (t) mm, respectively. The size of the washer on the column side was 60×60 mm. Both 12- and 15-mm bolts were used for beam and column specimen assembly. The arrangement of the bolt either at the top (T) or bottom (B) or both (D) locations on the cross-section of a beam member was also examined. Bolts were further reinforced with epoxy resin adhesives (E) by injection into gaps between the bolt and hole during the assembly process for both Japanese cedar and southern pine timber in some test conditions.

### Joint test of the beam and column assembly

Moment-resistance testing of the bolted joint in a T-shaped beam and column structure

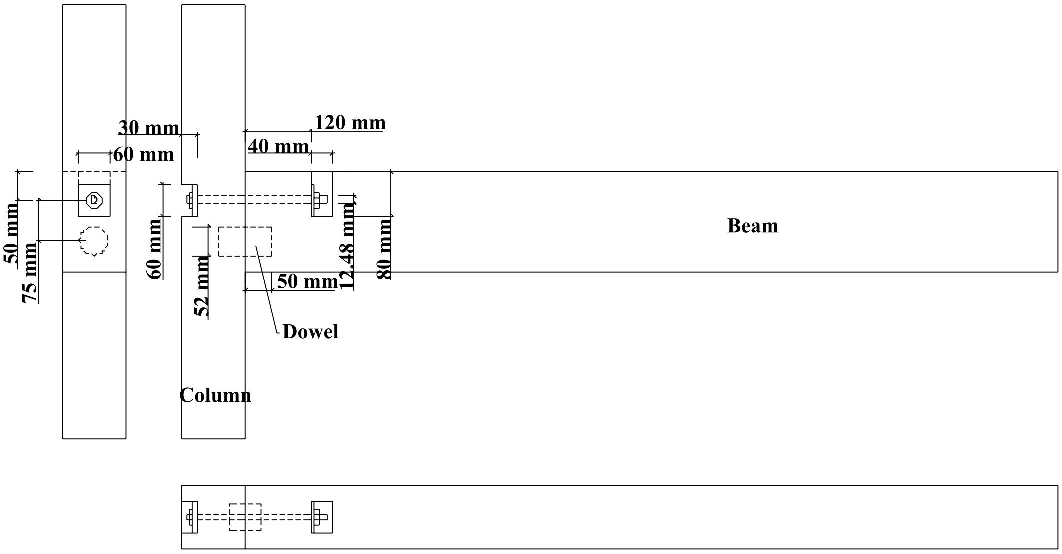

**Fig. 1. Beam and column joint configuration with 1 threaded rod at the top location.**

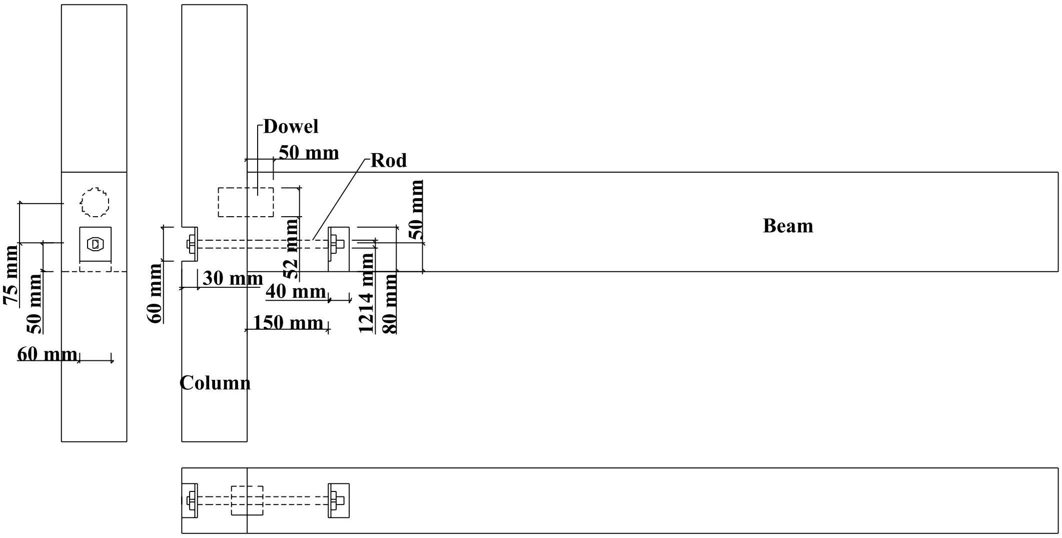

Fig. 2. Beam and column joint configuration with 1 threaded rod at the bottom location.

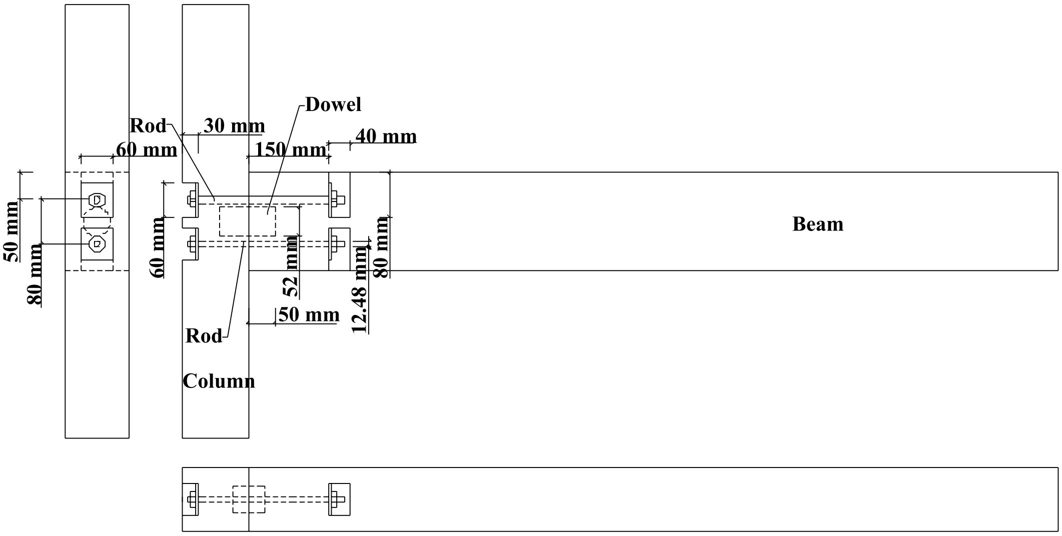

Fig. 3. Beam and column joint configuration with double threaded rods.

was performed as shown in Fig. 4. Specimens were fastened in different designated approaches, and a concentrated load was applied at a speed of 490 N·mm$^{-1}$ at the cantilevered member end. The span between the loading point and interface of the joint was 1260 mm, which was 7-times the beam depth to ensure acceptable bending moment behavior as suggested by Lin (1998). Each test condition had 4 replicates. The ultimate bending moment at rupture (M, kN·m) was obtained from the maximum load ($P_{max}$) and cantilever span. Flexural displacement (y) was recorded at 50 mm from the notches where the end of an embedded bolt was fixed with a nut and washer to estimate the internal rotation angle (θ, rad) of joints as follows:

$$\theta(\text{rad}) = y/d; \tag{1}$$

where d is the distance between the beam and column juncture and transducer location.

**Table 1. Experimental conditions of embedded threaded rods used for beam and column connections**

| Treatment | No. of rods | Diameter of rod (mm) | Size of washer (mm) | End distance in beam (mm) | Location of rod | Glue reinforcement |
|---|---|---|---|---|---|---|
| JT12-60-120[1)] | 1 | 12 | 60×60 | 120 | top | none |
| JT-12-60-150 | 1 | 12 | 60×60 | 150 | top | none |
| JT12-60-180 | 1 | 12 | 60×60 | 180 | top | none |
| JT12-50-150 | 1 | 12 | 50×50 | 150 | top | none |
| JT12-80-150 | 1 | 12 | 80×80 | 150 | top | none |
| JB12-60-150 | 1 | 12 | 60×60 | 150 | bottom | none |
| JT15-60-150 | 1 | 15 | 60×60 | 150 | top | none |
| JD12-60-150 | 2 | 12 | 60×60 | 150 | top/bottom | none |
| JT12-60-150E | 1 | 12 | 60×60 | 150 | top | epoxy |
| JD-12-60-150E | 2 | 12 | 60×60 | 150 | top/bottom | epoxy |
| ST12-60-150E | 1 | 12 | 60×60 | 150 | top | epoxy |
| ST12-60-180E | 1 | 12 | 60×60 | 180 | top | epoxy |
| SD-12-60-150E | 2 | 12 | 60×60 | 150 | top/bottom | epoxy |

J, Japanese cedar; S, southern pine; T, top; B, bottom; D, top/bottom; 12, 15, bolt diameters; 50, 60, 80, sizes of the washer; 120, 150, 180, embedded distances from the beam end.

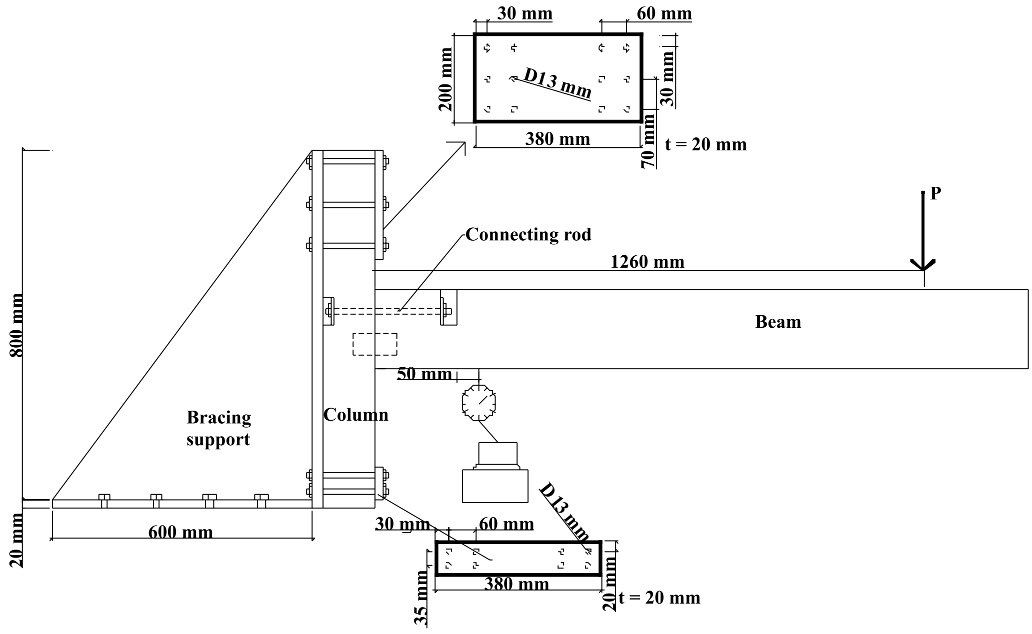

**Fig. 4. Configuration of a moment-resisting test for a T-shaped beam and column specimen fastened with an embedded rod.**

A moment-rotation coefficient (R) was then obtained as follows:

$$R = \theta/M. \qquad (2)$$

### Mechanical property evaluation of the wood

Compressive tests performed in a perpendicular wood fiber orientation followed the CNS453 standard (BSMI 2006). The compressive strength was then measured at 5% deformation of a specimen along the loading directions, i.e., tangential, radial, and 45° between 2 wood surfaces. The ultimate shearing stress parallel to the grain was tested according to the CNS455 standard. Shearing areas in both the tangential and radial directions were tested. Cleavage tests were done on both the radial and tangential surfaces of wood with the CNS 6716 standard. Each test condition had 12 replicates.

## RESULTS AND DISCUSSION

### Mechanical properties of the wood

Table 2 shows the basic mechanical properties of Japanese cedar and southern pine wood. The compressive stresses perpendicular to the grain measured in the radial direction ($F_{c\perp r}$) were higher than those measured in the tangential ($F_{c\perp t}$) and 45°-oriented ($F_{c\perp 45}$) cases for both wood species. The compressive stress of Japanese cedar was only 53.5% on average that of southern pine. Density may have been an important parameter influencing the mechanical properties, and the density of Japanese cedar was only 74.5% that of southern pine. A similar trend was noted for the shear strength of southern pine, being 45.5% higher compared to Japanese cedar specimens. However, no significant difference was found when the wood sheared between the radial and tangential faces. Further, the results of cleavage strength for both wood species and splitting in 2 different directions were similar and showed no influence due to the density parameter.

### Flexural properties of the beam and column joints

(I) Effect of the embedded length and washer size

The performance of the bending moment resistance of a beam and column joint without epoxy reinforcement was first evaluated using Japanese cedar members. With different embedded lengths of threaded rods, results showed that the joint with a rod embedded for 150 mm sustained a slightly higher load and bending moment at failure than those embedded for 120 mm (Table 3). This indicated that increasing the shear area of the wood by

**Table 2. Mechanical properties of the 2 wood species**

| Species | Density $kg \cdot m^{-3}$ | $F_{c\perp r}$[1] MPa | $F_{c\perp t}$ MPa | $F_{c\perp 45}$ MPa | $F_{vr}$ MPa | $F_{vt}$ MPa | $F_{spr}$ $kN \cdot m^{-1}$ | $F_{spt}$ $kN \cdot m^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Japanese | 410 | 7.64 | 6.08 | 4.51 | 6.47 | 7.06 | 24.4 | 29.1 |
| cedar | (60)[2] | (1.57) | (1.37) | (1.08) | (0.98) | (1.27) | (9.3) | (6.1) |
| Southern | 550 | 16.07 | 8.62 | 9.41 | 10.09 | 9.60 | 30.4 | 28.4 |
| pine | (60) | (4.51) | (2.06) | (1.47) | (1.76) | (2.06) | (6.6) | (2.4) |

[1] $F_{c\perp r}$, $F_{c\perp t}$, $F_{c\perp 45}$, compressive stress perpendicular to the grain tested in the radial, tangential, and 45° directions, respectively; $F_{vr}$, $F_{vt}$, shearing strength in the radial and tangential directions, respectively; $F_{spr}$, $F_{spt}$, cleavage strength in the radial and tangential directions, respectively.

[2] Values in parentheses are standard deviations.

**Table 3. Resisting bending moment properties of Japanese cedar beam and column joints with embedded threaded rods**

| Treatment | | Max. load (N) | Max. bending moment M (N·m) | Internal rotation angle (rad) | Moment-rotation coefficient R (rad·$N^{-1}$·$m^{-1}$) |
|---|---|---|---|---|---|
| JT12-60-120[1)] | Mean | 3206 | 4039 | 0.343 | 8.526E-05 |
| | Max. | 3269 | 4119 | 0.405 | 1.039E-04 |
| | Min. | 3095 | 3900 | 0.230 | 5.612E-05 |
| | C.V. (%) | 3 | 3 | 29 | 30 |
| JT-12-60-150 | Mean | 3638 | 4584 | 0.458 | 1.008E-04 |
| | Max. | 3965 | 4996 | 0.463 | 1.140E-04 |
| | Min. | 3222 | 4059 | 0.453 | 9.068E-05 |
| | C.V. (%) | 10 | 10 | 1 | 12 |
| JT12-60-180 | Mean | 2900 | 3654 | 0.515 | 1.422E-04 |
| | Max. | 3127 | 3904 | 0.527 | 1.634E-04 |
| | Min. | 2557 | 3223 | 0.508 | 1.297E-04 |
| | C.V. (%) | 10 | 10 | 2 | 13 |
| JT12-50-150 | Mean | 2595 | 3269 | 0.447 | 1.373E-04 |
| | Max. | 2732 | 3442 | 0.455 | 1.492E-04 |
| | Min. | 2384 | 3004 | 0.439 | 1.304E-04 |
| | C.V. (%) | 7 | 7 | 2 | 8 |
| JT12-80-150 | Mean | 2990 | 3767 | 0.464 | 1.232E-04 |
| | Max. | 3174 | 4000 | 0.470 | 1.262E-04 |
| | Min. | 2858 | 3601 | 0.455 | 1.174E-04 |
| | C.V. (%) | 6 | 6 | 2 | 4 |
| JB12-60-150 | Mean | 919 | 1158 | 0.461 | 3.989E-04 |
| | Max. | 977 | 1231 | 0.467 | 4.119E-04 |
| | Min. | 866 | 1091 | 0.450 | 3.794E-04 |
| | C.V. (%) | 6 | 6 | 2 | 4 |
| JT15-60-150 | Mean | 3137 | 3953 | 0.454 | 1.162E-04 |
| | Max. | 3443 | 4338 | 0.456 | 1.355E-04 |
| | Min. | 2668 | 3362 | 0.450 | 1.049E-04 |
| | C.V. (%) | 13 | 13 | 1 | 14 |
| JD12-60-150 | Mean | 3317 | 4179 | 0.431 | 1.031E-04 |
| | Max. | 4375 | 4378 | 0.469 | 1.138E-04 |
| | Min. | 3206 | 4039 | 0.378 | 9.359E-05 |
| | C.V. (%) | 4 | 4 | 11 | 10 |

J, Japanese cedar; S, southern pine; T, top; B, bottom; D, top/bottom; 12, 15, bolt diameters; 50, 60, 80, sizes of the washer; 120, 150, 180, embedded distances from the beam end; C.V., coefficient of variation.

extending the length of a rod benefited resistance to an external load. However, further extending the rod length to 180 mm did not provide a higher bending moment capacity for the joint. This might have been due to early compressive failure on the column member surface beneath the steel washer as pulled by the rod in tension. The larger internal rotation angle and moment-rotation coefficient of the beam and column joint embedded with a 180-mm threaded rod showed weaker stiffness.

Chang and Hsu (2005) studied the bending moment properties of a traditional post and beam structure with 75×117-mm members. The maximum bending moment of the commonly used Go-Dou joint was 706~1045 N·m with an average of 853 N·m. The column split at the mortise edge, and the beam showed shear failure at the sloped tenon when a load was applied. The bending moment was only about 23.9% of the average value of joints assembled with an embedded rod in this study, indicating the effectiveness of resisting a bending moment by the proposed fastener and assembly process. The other more-complicated stepped dovetail joint showed values of 580~1199 N·m with an average of 981 N·m of bending moment resistance in Chang and Hsu's (2005) report. Major failure occurred on the column member due to splitting at the mortise bottom that was fitted with the stepped dovetail of the beam member. Compared to the results in this study, the bending moment resistance was also only about 27.4% of that of the structure assembled with threaded rods. The wood wedges were pulled out from the mortise of both traditional joints causing low stiffness in the joints, and failure was due to the stress concentration.

When considering the effect of the washer size fastened onto the beam member side, the joint fastened with a 60×60-mm washer (JT-12-60-150) had better bending moment resistance than that with a 50×50-mm washer (JT-12-50-150). A 20% gain in shearing area was expected when using a 60×60-mm washer to resist the external load compared to a 50×50-mm washer. On the other hand, the joint fastened with the larger washer of 60×80 mm (JT-12-80-150) did not show further improvement. Similar early compressive failure also occurred on the column member surface receiving the compressive force from a fastened steel washer through the tension rod. Although neither washer size affected the internal rotation angle at the joint when a load was applied to the cantilever beam member, larger moment-rotation coefficients indicated weaker joint stiffness compared to the joint tightened with a 60×60-mm washer.

Wang (1993) reported that the compressive stress perpendicular to the grain of Japanese cedar was 5.68 MPa, which was much weaker than the compressive strength measured parallel to the grain at 21.36 MPa. In this study, the average compressive strength perpendicular to the grain for the 3 different loading directions was 6.08 MPa, which was similar to Wang's report and only 28.5% of the compressive strength measured parallel to grain. In fact, the major failure of a joint nearly always occurred on the column member side instead of the beam member side in most cases. Seventy percent of joints failed by crushing and splitting the wood at the bottom of the washer notches on the column member as shown in Fig. 5. Therefore, it is necessary to further determine an adequate size for the washer to provide a sufficient contact area against the required compressive resistance of wood column members.

### (II) Effect of the position, diameter, and number of threaded rods

The load-displacement relationship of Japanese cedar beam and column joint specimens is shown in Fig. 6. When an external force was applied to the cantilevered beam, the resultant bending moment at the joint was resisted through the threaded rod and the lower edge of the beam member end which rested against the surface of the column member. A high resisting moment could be obtained as the distance between the embedded rod and the lower beam edge increased. Usually better bending moment resistance of a beam and column joint was expected when the embedded rod was located on the upper side of a beam member. In this study, the bending moment of the beam and column joint fastened with a threaded rod located at the lower side of the beam member (JB-12-60-150) was only 25.3% that of the upper side condition (JT-12-60-150). The value of the moment-rotation coefficient of JB-12-60-150 was about 4-times that of the JT-12-60-150 joint, indicating weak stiffness of the joint. In the case when a larger threaded rod, i.e., 15 mm in diameter (JT-15-60-150), was used for the beam and column assembly, the bending moment capacity did not show any improvement compared to the joint fastened with a 12-mm rod. A similar internal rotation angle and moment-rotation coefficient of the beam and column joint resulted between 12- and 15-mm threaded rod conditions. This indicates that the tensile capacity of a 12-mm structural steel rod was sufficient to sustain the force from the resultant bending moment or was higher than the expected compressive force that the wood beneath the fastened washer could hold. However, some threads

**Fig. 5. Wood depression and split at the bottom of the washer notches on the column member.**

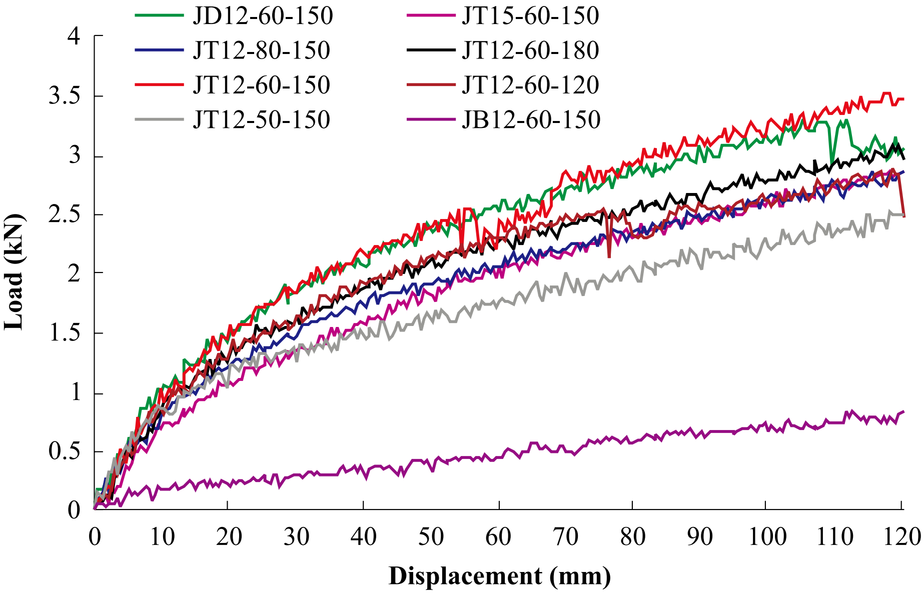

**Fig. 6. Load-displacement relationship of bending test for a Japanese cedar beam and column connected with hidden threaded rods. Codes are explained in the footnotes to Table 3.**

were stripped off in 4 of 32 test specimens when the rods were subjected to tension.

Further, a split occurred between the holes drilled for the threaded rod and dowel on the column member due to the pressure of a bent rod in some test specimens. This suggests that a larger spacing between the 2 holes needs to be considered.

When threaded rods were fastened at both the upper and lower sides of a beam member (JD-12-60-150), no further improvement in the bending moment resistance of the beam and column connection was found. Both the internal rotation angle and moment-rotation coefficient of the beam and column joint showed similar values those of a joint without an additional rod at the bottom of the beam member. This was due to the applied load mainly being resisted by the rod at the upper side of the beam and the critical joint failure still being controlled by the weak compressive stress perpendicular to the grain at the notch on the column member. However, this joint configuration may have better performance in resisting a cyclic load or a reversed moment. Although Lee et al. (2007) reported better rotational stiffness for traditional tenon and mortise joints, the values would be reduced if the initial slip due to the fit between column and beam members was also included in the integral joint performance estimation.

(III) Effects of epoxy reinforcement

To investigate the effects of epoxy reinforcement on the flexural performance of a joint, both Japanese cedar and southern pine members were used for the beam and column assembly. The size of the washer on the column member was increased to 12 (thick) × 120 (wide) × 200 (long) mm to reduce potential compressive failure perpendicular to the grain. Two 15-mm wood dowels instead of one 52-mm dowel were further used to hold the beam member during assembly. Dowel holes were then drilled on the side of the column to prevent the wood grain from splitting from the threaded rod hole directly to the dowel holes when the rod bent during the test. Results indicated that the bending moment resistance of the Japanese cedar member joint with 2 embedded threaded rods (JD-12-60-150E) improved 39.5% with additional epoxy reinforcement (Table 4). The internal rotation angle and moment-rotation coefficient were reduced 21.6 and 40.6%, respectively, indicating a stiffer joint. This shows that modification of the washer size and prevention of splitting by changing the layout or spacing of the holes on the column were effective. Southern pine beam and column joints with epoxy reinforcement also showed 16.3 and 25.1% higher bending moment resistance than those of Japanese cedar joints with 1 and 2 embedded threaded rods, respectively, but without epoxy application. However, after epoxy reinforcement application to Japanese cedar beam and column joints, they showed similar bending resistance to southern pine member joints. The results also demonstrated that the moment-rotation coefficient was reduced to $4.757 \times 10^{-5}$rad. $N^{-1}$ $m^{-1}$, only 31.6% of the value of the joint without epoxy reinforcement. Furthermore, the highest bending moment capacity was obtained for the southern pine joint when the embedded length of threaded rods was extended up to 180 mm (ST12-60-180E).

Failure of beam and column joints with epoxy reinforcement occurred mainly by stripping the threads of rods in tension. This confirms the effectiveness of using larger washers to deal with the weak compression performance of a column member. A wood surface depression at the notch bottom due to a compressive force perpendicular to the

**Table 4. Resisting bending moment properties of beam and column joints reinforced with epoxy adhesive**

| Treatment | | Max. load (N) | Max. bending moment M (N·m) | Internal rotation angle (rad) | Moment-rotation coefficient R (rad·N$^{-1}$·m$^{-1}$) |
|---|---|---|---|---|---|
| JT12-60-150E | Mean | 3728$^{b}$ | 4697$^{b}$ | 0.275$^{a}$ | 5.816E-05$^{ab}$ |
| | Max. | 4139 | 5215 | 0.435 | 8.706E-05 |
| | Min. | 3317 | 4179 | 0.168 | 4.024E-05 |
| | C.V. (%) | 10 | 10 | 42 | 38 |
| JD-12-60-150E | Mean | 4396$^{b}$ | 5538$^{b}$ | 0.338$^{a}$ | 6.123E-05$^{a}$ |
| | Max. | 4850 | 6111 | 0.377 | 6.656E-05 |
| | Min. | 3886 | 4896 | 0.298 | 5.492E-05 |
| | C.V. (%) | 11 | 11 | 9 | 8 |
| ST12-60-150E | Mean | 4230$^{b}$ | 5330$^{b}$ | 0.194$^{a}$ | 3.619E-05$^{b}$ |
| | Max. | 4629 | 5832 | 0.218 | 4.118E-05 |
| | Min. | 3902 | 4916 | 0.131 | 2.667E-05 |
| | C.V. (%) | 7 | 7 | 22 | 18 |
| ST12-60-180E | Mean | 5277$^{a}$ | 6649$^{a}$ | 0.279$^{a}$ | 4.048E-05$^{ab}$ |
| | Max. | 5972 | 7525 | 0.442 | 5.868E-05 |
| | Min. | 4407 | 5553 | 0.118 | 2.124E-05 |
| | C.V. (%) | 12 | 12 | 59 | 52 |
| SD12-60-150E | Mean | 4150$^{b}$ | 5230$^{b}$ | 0.220$^{a}$ | 4.181E-05$^{ab}$ |
| | Max. | 4739 | 5972 | 0.251 | 4.852E-05 |
| | Min. | 3601 | 4537 | 0.155 | 3.423E-05 |
| | C.V. (%) | 11 | 11 | 20 | 14 |

J, Japanese cedar; S, southern pine; T, top; D, top/bottom; 12, bolt diameter; 60, sizes of the washer; 150, 180, embedded distance from beam end; C.V., coefficient of variation.
Ducan's grouping, $\alpha = 0.05$, a > b.

grain was no longer found on the column member. On the other hand, the benefit of using the higher-density southern pine rather than Japanese cedar was insignificant because critical failure was mainly located on the threaded part of the rods. More threads on the rod might need to be fastened to hold the joint together by increasing the number of nuts. For all test specimens, no failure in shear occurred at the beam end where a compressive force parallel to the grain was applied through the washer. This indicates that the end distance or embedded length of a rod of 120~180 mm was acceptable for holding a threaded rod.

## CONCLUSIONS

A threaded rod can be embedded between beam and column members to improve the structural performance of a joint for traditional wood framing without the fastener itself showing on the structure surface. More-effective bending moment resistance of a beam and column joint was found when the threaded rod was embedded at the upper location of the cross-section on the beam member rather than at the bottom location. The critical failure of a joint tightened with an embedded rod may have been due to the weak compressive strength perpendicular to the grain on the column member, and was improved by enlarging the size of the washer to hold the beam member through the tension rod. Concerning the horizontal shear resistance of a beam member subjected to a bending moment, the end distance or embedded length of a rod of 120~180 mm was acceptable for holding a tension rod to prevent wood shear failure. The bending moment capacity could be further improved by reinforcing the joint with epoxy glue in the rod holes. While a similar structural performance of reinforced joints was found between Japanese cedar and southern pine species, the failure of stripped threads on the rods should be considered. The results also indicated that a lower moment-rotation coefficient or stiffer joint could be obtained with epoxy reinforcement application.

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