DESTRUCTIVE TESTING OF METAL-PLATE-CONNECTED WOOD TRUSS JOINTS

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ABSTRACT: Load-displacement characteristics and failure modes of metal-plate-connected wood truss joints are presented. Tension splice, heel, and web at the bottom chord joints are fabricated using southern pine (SP) no. 2 lumber and 20-gage punched metal plates. These joints are tested with a newly developed testing apparatus that allows the testing of all three joints without major modifications. In-plane loads are applied to simulate the loads carried by truss members. The computerized testing apparatus and methods show potential as an efficient testing procedure to assess joint behavior. The average strength of tension splice, heel, and web at the lower chord joints is 27.0 kN, 22.7 kN, and 16.7 kN, respectively. The failure of the heel joint is characterized as ductile, and that of the tension splice and web at the bottom chord joints as brittle. The failure of the joints is a combination of wood and teeth failure. The results are useful for semirigid joint analysis and design of metal-plate-connected wood trusses.

INTRODUCTION

Metal-plate-connected wood trusses have been used for floors and roofs for the past 30 years. Conventional procedures for the analysis and design of these trusses are based on the assumption that the member end connections are either pinned or completely rigid. These assumptions are not entirely consistent with practical conditions. However, they have been accepted because of the simplicity in analysis and design. The actual joints of metal-plate-connected wood trusses can be characterized as semirigid. These joints allow some relative movement (axial, translation, and rotation) between the joined members in the plane of the truss due to concentric or eccentric forces in the members. Joint deformation (axial or rotational) can be responsible for a substantial proportion of the overall deformation of a structure and it often has a significant bearing on the internal force distribution. Methods applicable to the analysis of structures with flexible connections are not scarce but lack the availability of structural characteristics (strength and stiffness) of joints. Structural characteristics of these joints must be derived from full-scale load tests to be used as input for improved analysis and design of trusses.

Today, joint testing standards include the American Society of Testing and Materials (ASTM) D1761, (“Standard” 1977) and the Canadian Standard Association (CSA) S347 (“Methods” 1980). The ASTM standard includes only one standard joint configuration, while the CSA standard includes four standard configurations at various orientations of plate and wood grain to loading direction. These configurations do not realistically simulate actual truss-joint action under combined bending and axial loadings.


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Published strength and stiffness data on metal-plate-connected truss joints are scarce. Several researchers (Quaile and Keenan 1979; McLain 1983; Gupta and Gebremedhin 1988) have emphasized the need for testing of actual truss joints to determine their structural characteristics and failure modes. Some testing of metal-plate truss joints has been performed by metal-plate manufacturers, but this proprietary data has not been made public.

Few investigators (Misra and Esmay 1966; Suddarth et al. 1979; Heard et al. 1988) have tested tension splice joints under pure axial tension. Maragechi and Itani (1984) tested tension splice joints in pure axial tension, pure shear, and pure bending to obtain the stiffness of the joints. They reported that axial and rotational stiffness of a joint have an appreciable influence on member end forces, while shear stiffness has little effect. Sheppard (1969) tested heel joints and compared six different sizes of metal plates. He reported that the most common mode of failure was teeth withdrawal. Recently, Lau (1987) obtained the strength and stiffness values for heel joints from actual tests to use in a computer program for analysis of wood frames. No studies have been reported on testing of web at the lower chord joints. McLain (1983) provided an excellent overview of the research needs for mechanical fastening of structural wood members.

This paper describes the method developed for testing of actual metal-plate-connected wood truss joints using a novel testing apparatus. This is the first report of ongoing research in probabilistic design of metal plate connected wood trusses. The major objectives of this paper are:

1. To develop and construct a novel computer-controlled testing apparatus and method for testing metal-plate-connected wood truss joints.
2. To conduct destructive testing of actual truss joints. Heel, tension splice, and web at the lower chord joints were tested.
3. To determine the strength and stiffness values of the joints to be used in a computer program for analysis and design of wood trusses.
4. To characterize failure modes.

Once the strength and stiffness of joints are determined, the element stiffness matrix of truss members can be modified to include the stiffness of the connections. This analysis would provide more accurate forces and moments of truss members.

**APPARATUS AND TEST PROCEDURE**

**Material and Joint Fabrication**

All lumber used for the fabrication of the test specimens was 38 × 89-mm Southern Pine no. 2 kiln dry (KD) 15 purchased from a local lumber company. All metal plates were supplied by Alpine Engineered Products, Inc. The tension splice joints were fabricated by pressing 76.2 × 101.6-mm metal plates using a hydraulic press. The heel and web joints were fabricated by pressing 76.2 × 127-mm metal plates using rollers. All joints were fabricated by commercial truss manufacturers. The specifications for the plates are given in Table 1. All joints were designed for an 8.5-m span Fink truss with 5/12 roof slope.
Testing Apparatus

A novel truss-joint testing apparatus and computerized data-acquisition method were developed. The testing apparatus provided the flexibility to test different truss joints without major modifications. The testing procedure and data acquisition were computer-controlled. The testing apparatus consisted of a horizontal rigid frame bolted to the floor at five places. The testing of the truss joints was done with a test specimen supported by and loaded on this rigid test frame. The test frame also supported reaction fixtures, links, restraints, and hydraulic cylinders.

The load was applied through hydraulic cylinders. A system of calibrated force transducers attached to the hydraulic cylinders measured the force in the members forming the joints. The cylinders were actuated by a single-variable volume hydraulic pump and were restrained by the test frame to exert pressure on the joints. A proportional solenoid pressure control valve was the “heart” of the system, permitting close control of the pressure in the cylinders and thereby the forces exerted by the cylinders. Displacements of the test specimens were monitored using two linear variable differential transformers (LVDTs). An IBM-PC/PS2 (Model 50) computer and a data-acquisition system controlled the applied force and recorded the data. The analog signals from load cells and LVDTs were amplified using a signal conditioning unit and then converted into digital signals by an analog-to-digital (AD) converter to be recorded by the computer.

The three types of joints tested were the tension splice, heel, and web at the bottom chord.

Tension Splice Joints

Fifty-two joints were tested in axial tension. The test frame with a tension-splice joint specimen in place is shown in Fig. 1. The load simulating the axial tensile force at the bottom chord was applied by two hydraulic cylinders connected in parallel. The cylinders were double-acting and had a 76-mm bore by 203-mm throw. Rod-end–type, strain-gage load cells were threaded onto the piston rods of the cylinders. Both load cells were connected to specially designed friction plates through a link. The test specimen was sandwiched between two friction plates. The plates were coated with polyurethane, a very high friction material, to develop the necessary grip. The other end of the test specimen was similarly sandwiched between friction plates and the plates were then connected to the test frame by a link.
Axial displacement of the joint was measured at both sides of the joint using two LVDTs as shown in Fig. 1.

Web at the Bottom Chord Joints
Fifty-five webs at the bottom chord joints were tested. The test setup for the web at the bottom chord joint is shown in Fig. 2. A compressive force was applied to one of the web members and a tensile force was applied to the other web member. The applied forces were measured by two load cells connected by links to the cylinders at one end and to the members at the other. The bottom chord was connected to the frame at the two ends. Two LVDTs measured the deflections along the longitudinal axes of the web members.

Heel Joints
Fifty-six heel joints were tested. The test setup for the heel joints is shown in Fig. 3. The compressive force was applied at the top chord. The bottom chord was attached to the frame by a link and subjected to a tensile force equal to the horizontal component of the compressive force. The compressive and tensile forces were measured by load cells as shown in Fig. 3. From static equilibrium, the vertical component of the compressive force was the reaction at the roller support. Two LVDTs, one to measure the displacement of the joint and the other to measure the rotation of the top chord relative to the bottom chord, were used in these tests.

Testing Procedure
Before fabricating the joints, 250 pieces of lumber were nondestructively tested for modulus of elasticity (MOE). Each piece was 2.44 m long and was tested in static flatwise bending using a concentrated dead load at mid-span. After testing the joints, six pieces (38 × 38 × 89 mm) were randomly cut from six different specimens to measure their specific gravity and moisture content. ASTM standards D2016-74, method A (ASTM: “Standard” 1974) and D2395-83, method A (ASTM: “Standard” 1983) were used to determine the moisture content and specific gravity, respectively.

The test specimens were fabricated seven days prior to testing and were
stored in a relatively uniform environment. Each test specimen was loaded such that its deformation is unrestrained in the load plane. The loading procedure was as follows:

1. Initialize the system. This procedure applies an initial minimum line pressure of 345 kPa in the cylinders, which corresponds to about 890 N of force in the test specimen. Even though this preloads the test specimen, deflection was set to zero.
2. Read load cells and LVDT's signals (in volts) after 8 sec. The signals were stabilized within this period of time.
3. Apply load increment. Loads were applied in equal increments from zero to failure. The increment of loading was chosen so that failure would occur in about 12 min. This procedure provided a sufficient number of readings to determine the load-deflection curve.
4. Convert volt signals into actual forces and displacements, print, and store
the data read in step 2. This procedure was completed in 2 sec.

5. Terminate loading when the deflection increased with no detectable increase in load-cell readings (failure) or go back to step 2.

The testing period for each specimen lasted for 12 min. This is consistent with the ASTM D1761-77 ("Standard" 1977) recommendation that failure should occur between 5 and 20 min. These testing procedures were followed for all the joints tested.

**EXPERIMENTAL RESULTS AND ANALYSIS**

The average modulus of elasticity (MOE) of the 250 pieces of lumber tested ranged from 4.1 GPa to 17.5 GPa with a mean value of 9.7 GPa and a coefficient of variation (CV) of 24.7%. The specific gravity and moisture content were 0.48 (CV = 14.6%) and 10% (CV = 3.5%), respectively.

The relationships between the applied load \((P)\) and joint deflection \((\Delta)\) for the tension splice, heel, and web at the bottom chord joints are shown in Fig. 4. All tests exhibited a nonlinear \(P-\Delta\) relationship. The average ultimate load, deflection at failure, stiffness, and their failure modes are tabulated in Table 2. Stiffness was defined as the ratio of the design load and the deflection at the design load. The design load was taken as the ultimate load divided by a factor of three, which includes a load duration factor for test load duration of 12 min and a factor of safety. The results of the experiments are discussed in the following.

**Tension Splice Joints**

A typical nonlinear load-displacement curve for a tension splice joint is shown in Fig. 4. Each value of displacement is an average of two values.

![Graph](image)

**FIG. 4. Load-Displacement Curve for Three Types of Joints**
TABLE 2. Means and Coefficients of Variation of Ultimate Strength, Deflection at Failure, and Stiffness and Failure Modes for Three Types of Joints Tested

<table>
<thead>
<tr>
<th>Joint type (1)</th>
<th>Mean ultimate load (kN) (2)</th>
<th>Deflection at failure (mm) (3)</th>
<th>Stiffness (kN/m) (4)</th>
<th>Failure mode (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>27.0 (52, 17.6%)</td>
<td>1.91 (52, 22.1%)</td>
<td>5.28 × 10⁴ (50, 18.3%)</td>
<td>Wood tearing and teeth failure</td>
</tr>
<tr>
<td>Web</td>
<td>16.7 (55, 17.1%)</td>
<td>2.23 (53, 28.1%)</td>
<td>4.12 × 10⁴ (50, 52.0%)</td>
<td>Teeth failure at the tension web</td>
</tr>
<tr>
<td>Heel</td>
<td>22.7 (56, 06.7%)</td>
<td>7.60 (45, 09.4%)</td>
<td>0.38 × 10⁴ (44, 10.4%)</td>
<td>Teeth failure at the bottom chord</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses are number of observations and coefficient of variation, respectively.

measured at each side of the joint. The loading rate was approximately 2,200 N/min. The average strength and stiffness and their CV are shown in Table 2. The average failure load ranged between 13.8 and 36.8 kN. The data of two test specimens were not included in calculating the stiffness of the joints because initial displacement readings were incorrectly measured by the LVDT. The coefficients of variation for the ultimate load and deflection at failure were 17.6% and 22.1%, respectively. The stiffness of the joint varied between $3.24 \times 10^4$ and $7.79 \times 10^4$ kN/m. This range illustrates the variability of the strength and stiffness properties of the joints. This variation may be attributed to the large variation in the properties of the lumber and perhaps to possible variation in fabrication of the test specimens. This information is essential for a probabilistic approach to design of wood trusses.

The most common mode of failure was a combination of wood and metal-plate teeth failure. The mode of failure can be characterized as follows. As the loading progressed, the row of teeth near the joint gap started to bend and crush the wood against which they bear. It should be noted that the section at the row of teeth near the gap is critical because the total load is transferred by shear at this section. The joints failed by wood tearing near the joint gap and teeth withdrawal occurred at the two ends of the plate. The tearing of wood was usually initiated at the first row of teeth, although sometimes it was initiated at the second or third row. The failure of tension splice joints was sudden and can be characterized as brittle. All of the test specimens tested in axial tension failed in this fashion with the exception of two specimens that failed in plate tension. Typical failure modes are shown in Fig. 5(a). Note that for other size of plates, the mode of failure may be different because of size effect.

Web at the Bottom Chord Joints

A total of 55 webs at the bottom chord joints were tested. A typical load-displacement curve for a web at the bottom chord joint is shown in Fig. 4. The load is the resultant of the tension and compression forces in the two web members. To plot the $P-\Delta$ curve, the displacement along the tension web member was taken instead of the displacement along the resultant force. The displacement along the tension web member only was taken because this member translated much more than the compression web member when the forces were applied. The compression web member hardly translated because it bears against the bottom chord. The average strength values are
FIG. 5. (a) Failure Modes for Tension Splice Joints (Wood and Teeth Failure, Plate Tension Failure, and Teeth Failure)

Teeth failure

Plate tension failure

Wood and teeth failure

1978
FIG. 5. (b) Failure Modes for Web at Bottom Chord Joints (Teeth Failure)
given in Table 2. The strength for this joint varied from 8.7 kN to 22.7 kN. The stiffness of the joints ranged from $1.69 \times 10^4$ kN/m to $12.7 \times 10^4$ kN/m. The coefficients of variation for the ultimate load and deflection at failure were 17.1% and 28.1%, respectively.

For two test specimens, displacements were not measured (we forgot to place LVDTs), and 53 displacement values were therefore used to calculate the mean for deflection at failure. Only 50 stiffness values were used to determine the mean because, for three more test specimens, initial displacement values were incorrectly measured by the LVDTs.

The most common mode of failure observed was that of teeth failure at the tension web member. This was because only one-fourth of the plate was in contact with the tension web member resulting in very few teeth holding it. The teeth at the tension web started to bend as the load was increased and finally the web member pulled out. The failure of the web at the bottom chord joint was sudden and can be characterized as brittle. The typical failure modes are shown in Fig. 5(b).

**Heel Joints**

A total of 56 heel joints were tested. A typical load-displacement curve for a heel joint is shown in Fig. 4. The load represents the compressive force
in the top chord and the displacement is the value measured in the direction of the load. The average strength of the joints tested is shown in Table 2. Strength for the heel joint was defined as the maximum compressive force in the top chord because this force governed the failure of the joint. The failure load varied from 19.3 kN to 25.6 kN. The stiffness of the joints ranged from $0.28 \times 10^4$ to $0.45 \times 10^4$ kN/m. The coefficients of variation for the ultimate load and deflection at failure were 6.7% and 9.4%, respectively.

For the first 11 test specimens the displacement measurements were incorrect due to wrong placement of the LVDTs. Therefore, these displacement values including deflection at failure, were not included in the analysis. One more test specimen's initial displacement data could not be used for stiffness calculation because the initial displacement readings were incorrectly measured by the LVDTs. The rotation of the top chord relative to the bottom chord was measured but it turned out to be negligible.

The most common mode of failure for the heel joint was teeth failure at the bottom chord. The failure phenomenon was the same as that of the tension splice joints except that there was no wood failure. The teeth were bent almost 45° and pulled out entirely from the bottom chord. The failure initiated near the joint gap where the top and bottom chords come together. The failure of the heel joint was not sudden and sign of failure was visible. Therefore, the failure of the heel joint can be described as ductile. Typical failures of the heel joint are shown in Fig. 5(c).

CONCLUSIONS

The following conclusions may be stated on the basis of this study:

1. A novel and versatile computer-controlled testing apparatus and data-acquisition system was developed to test actual metal-plate-connected tension splice, heel, and web at the bottom chord wood truss joints subjected to axial loading conditions.

2. The load-deflection characteristics of the joints tested were nonlinear.

3. The average strength and stiffness values for the joints were tension splice joint 27.0 kN and $5.28 \times 10^4$ kN/m, web at the bottom chord joint 16.7 kN and $4.12 \times 10^4$ kN/m, and heel joint 22.7 kN and $0.38 \times 10^4$ kN/m, respectively.

4. The failure of the heel joints can be characterized as ductile. The failure of the tension splice and web at the lower chord joints can be characterized as brittle.

5. The most common mode of failure was a combination of wood and teeth failure.

6. The variability of ultimate load of the heel joints was much lower (CV = 6.7%) as compared to the tension splice joints (CV = 17.6%) and the web at the bottom chord joints (CV = 17.1%). The CV for deflection at failure of the heel, tension, and web at the bottom chord joints were 9.4%, 22.1%, and 28.1%, respectively.

7. The results presented here apply to the plate type and sizes referred in this paper.

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APPENDIX. REFERENCES


1982