3. EXPERIMENTAL TEST AND RESULTS

3.1 INTRODUCTION

Two experimental tensile tests were conducted to investigate the actual double angle behavior under axial tensile loads. The results of these tests are used for verification of the 3D finite element model analysis. For this purpose, several factors are compared to each other, such as the load-displacement relationship and the initial stiffness.

3.2 TEST SETUP AND PROCEDURE

A 3/8 in. thick plate was connected to an equivalent W14x90 column with a double angle connection. L5x3x1/4 and L5x3x1/2 angle sections were used for the double angle connection. Each outstanding leg of the angle was connected to the column with four 3/4 in. diameter A325-N bolts. Each back-to-back leg of this angle was connected to the 3/8 in. thick plate with 3/16 in. E70XX fillet welds. The test setup is shown in Figure 3.1. A universal type testing machine was used to apply the tensile load. Use of the machine required that 1/2 in. thick plates be connected to each side of the 3/8 in. thick plate with 5/16 in. welds.

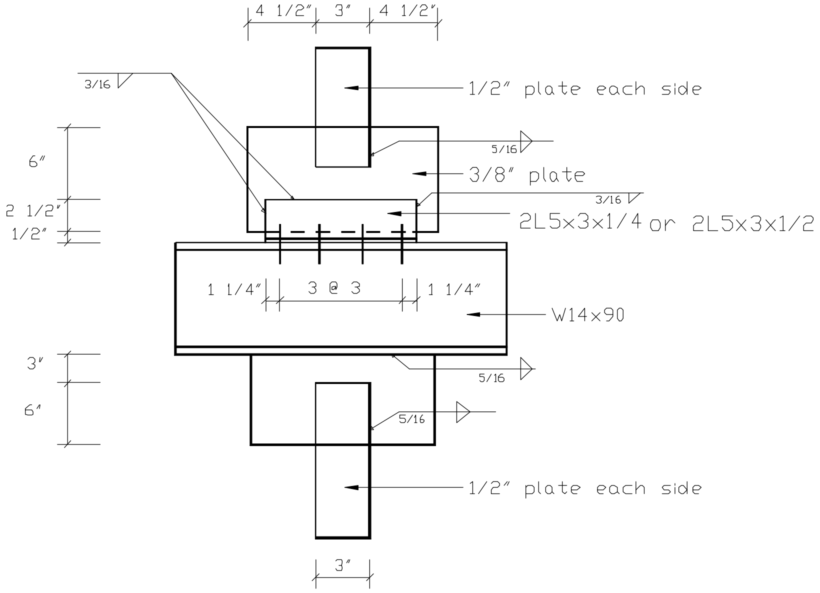


Figure 3.1 Axial Tensile Test Specimen

To measure bolt tension, two bolts were instrumented and calibrated. A "bolt gage" was installed in a 2 mm diameter hole drilled into the unthreaded portion of the bolt shank. Epoxy adhesive was injected into the hole and cured for approximately 12 hours at room temperature. The bolt was then baked for 3 hours at 285°F to form a tight bond between the strain gauge and bolt hole. After the above procedure was completed, each bolt was calibrated to obtain the load-strain relationship by applying tension using the universal test machine.

Axial tensile loading was applied to the outstanding leg of an angle through the 3/8 in. thick plate. The axial tensile loads were applied up to the yielding of the outstanding leg of the double angle connection. All the data was collected by using a PC-based data acquisition system, and analyzed by commercial software.

The two instrumented A325 bolts were tightened to 28 kips to satisfy the minimum bolt tension force prescribed in AISC Specification (1994). These bolts were placed in the bolt 1 and bolt 3 positions as shown in Figure 3.2. F436 circular washers were used for the 3/4 in. diameter bolt in the experimental tests. The nominal outside diameter of this washer is 1-15/32 in. Two dial gages were placed near the end of the angle to measure the displacements of the corner of the angle.

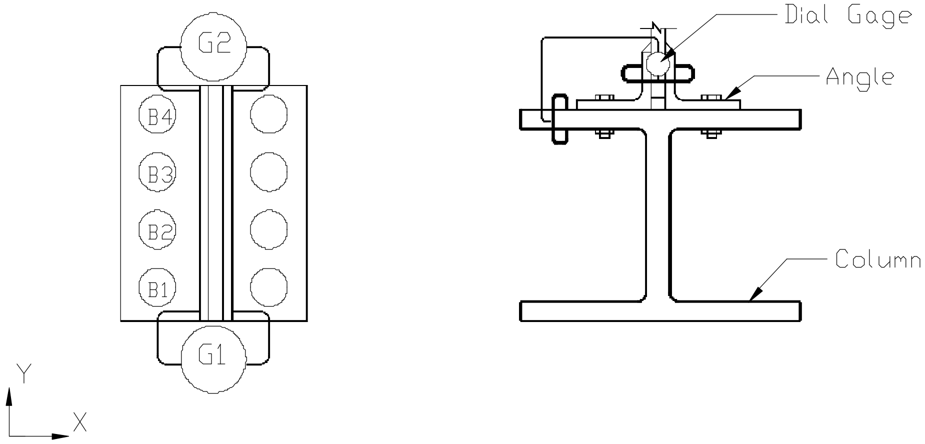


Figure 3.2 Locations of the Gage Instrumented Bolts and the Dial Gages

3.3 LIMIT STATES OF DESIGN

To estimate the ultimate strength of the L5x3x1/4 double angle connection, several limit states were checked using the AISC LRFD Specification and Manual (1994) as follows:

For simulated beam web connection,

<u>weld</u>

$$\begin{aligned}\phi R_n &= \phi\; t_e(0.60F_{EXX})(length\, of\;\; weld)\\ &= 0.75(\frac{3}{16})(42)(11.5)\\ &= 67.9\; kips/in.\end{aligned}\tag{3.1}$$

<u>simulated beam web shear strength at weld</u>

$$\begin{aligned}web\; strength &= \phi\,(0.6F_y t_w)(length\, of\;\; weld)\\ &= 0.9(0.6\times 50\times\frac{3}{8})(11.5)\\ &= 116.2\; kips/in.\end{aligned}\tag{3.2}$$

For the column flange,

<u>tension strength of the bolt</u>

$$\begin{aligned}\phi R_n &= \phi\;\; F_u^b(0.75A_b)\\ &= 0.75(120)(0.75\times 0.4418)\\ &= 29.8\, kips/bolt\end{aligned}\tag{3.3}$$

For angle specimen,

<u>tension yielding of the angle</u>

$$\begin{aligned}\phi R_n &= \phi F_y A_g\\ &= 0.9(36)(11.5\times 0.25)\\ &= 93.2\; kips\end{aligned}\tag{3.4}$$

bending of the angle

The ultimate tensile load, T_u, can be calculated from the bending of the outstanding leg of an angle. In the calculation of the ultimate tensile load, T_u, the applied tensile load is assumed to act at the end of the back-to-back leg of an angle as shown in Figure 3.3. The ultimate tensile load, T_u, can be calculated as follows:

$$2M_p - T_u b = 0 \tag{3.5}$$

where,

$$M_p = \frac{lt^2}{4}\sigma_y$$

Then,

$$\begin{aligned} T_u &= \frac{2}{b}\left(\frac{lt^2}{4}\sigma_y\right) \\ &= \left(\frac{lt^2}{2b}\right)\sigma_y \\ &= \left(\frac{11.5 \times 0.25^2}{2 \times 3.475}\right)(36) \\ &= 3.7\ kips \end{aligned} \tag{3.6}$$

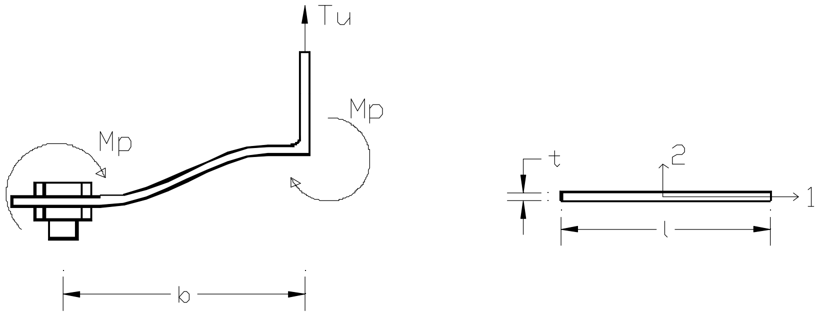


Figure 3.3 Configuration of the Outstanding Leg of an Angle due to Tension Loading

Considering the above equations for the given test specimen, the governing limit state is the bending of the angle. The ultimate strength for one angle is 3.72 kips for the L5x3x1/4 double angle connection.

The ultimate strength of the L5x3x1/2 double angle connection can be checked by the same limit state as the L5x3x1/4 double angle connection. For the L5x3x1/2 double angle connection, the governing limit state is also the bending of the angle by inspection. The ultimate strength for one angle can be calculated as follows:

$$2M_p - T_u b = 0 \tag{3.7}$$

Then,

$$\begin{aligned} T_u &= \frac{2}{b}(\frac{lt^2}{4}\sigma_y) \\ &= (\frac{lt^2}{2b})\sigma_y \\ &= (\frac{11.5\times 0.5^2}{2\times 3.35})(36) \\ &= 15.5\ kips \end{aligned} \tag{3.8}$$

3.4 COUPON TESTS USING L5x3x1/4 ANGLES AND L5x3x1/2 ANGLES

Before the actual tensile tests, two coupon tests were conducted to evaluate the material properties of the steel used for the test specimens. The yield stress of the L5x3x1/4 angle specimen was found to be 48.9 ksi, while that of the L5x3x1/2 angle specimen was found to be 49.2 ksi. Figure 3.4 shows the stress-strain relationship from the coupon tests.

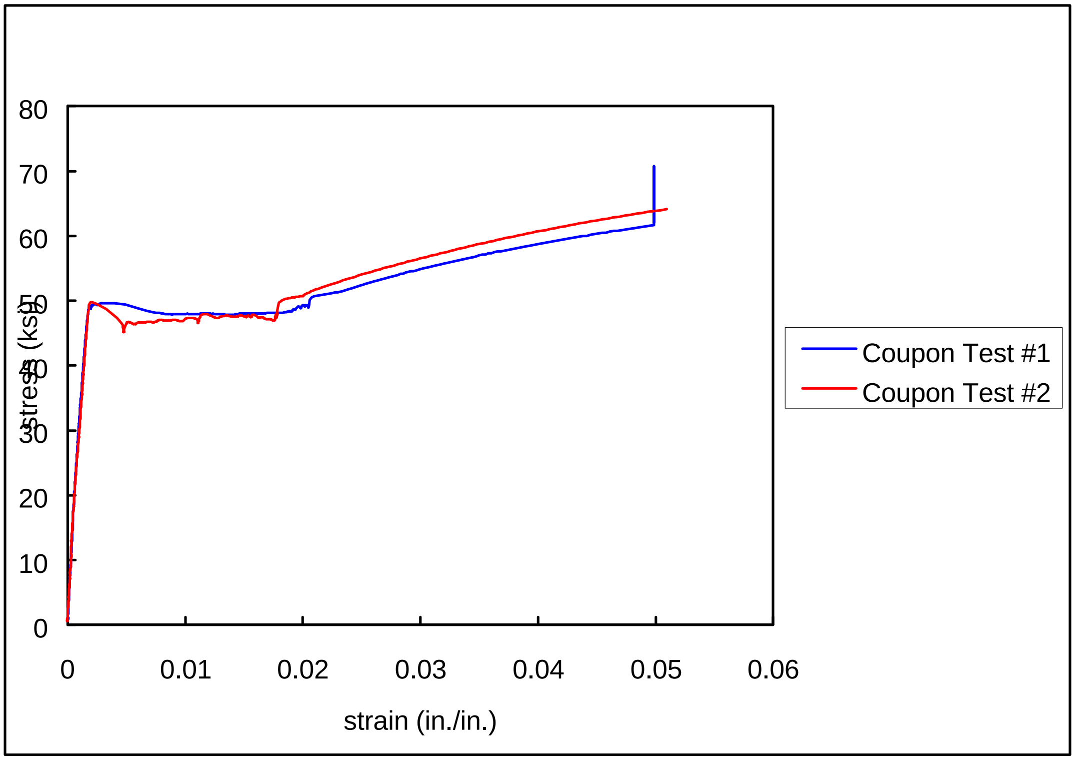


Figure 3.4 Stress-Strain Relationship for the Coupon Tests

3.4.1 Coupon Test Using L5x3x1/4 Angles

Since the actual yield stress of the L5x3x1/4 angle specimen was 48.9 ksi., the 3D finite element model was executed again to investigate the load-displacement relationship and the initial stiffness of the angle tested.

Figure 3.5 shows the load-displacement relationship of this double angle connection under axial tensile loads. The load-displacement curve of the experimental test shows good agreement with that of the 3D finite element analysis. The initial stiffness is 166.7 kips/in. from the load-displacement curve of the actual test, while that of the 3D finite element analysis is 133.0 kips/in. During the experimental test, yield lines formed along the edge of the washers. Considering the results of this experimental test, the failure of this double angle connection is due to the yielding of the outstanding leg of the angle.

Figure 3.6 shows the deformed shape of the L5x3x1/4 double angle connection and the von Mises stress diagram at the applied load of 16.16 kips from the 3D finite element analysis. The yielding zones formed along the edge of the bolt and the corner of the angle. Table 3.1 contains the data for the load-displacement relationship of the 3D FEM L5x3x1/4 double angle connection under axial tensile loading.

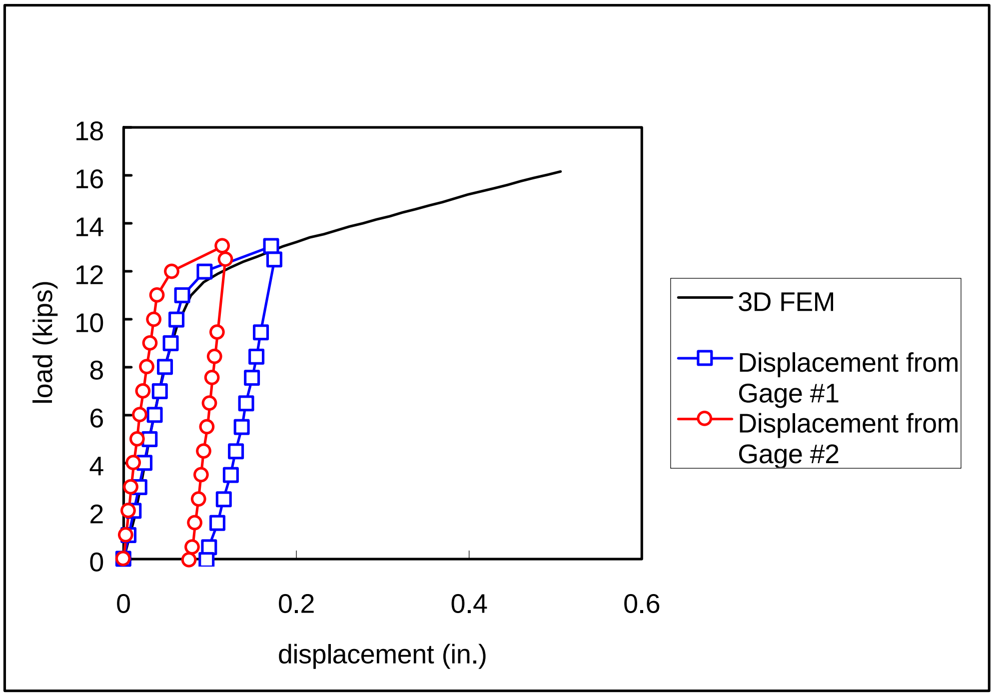
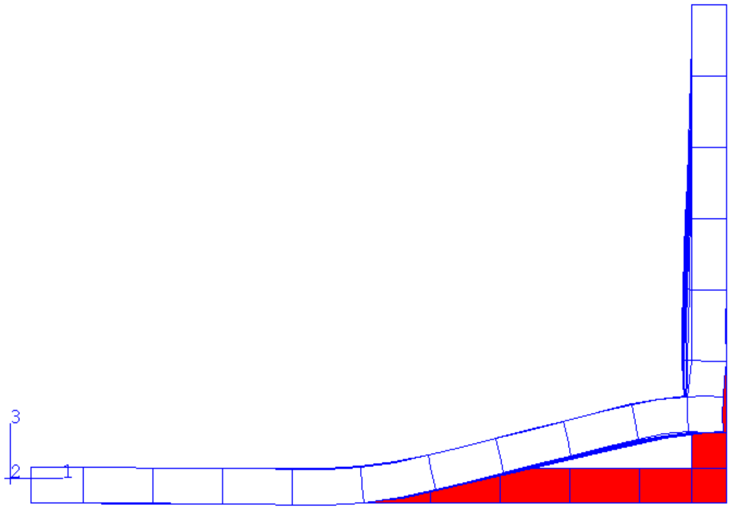
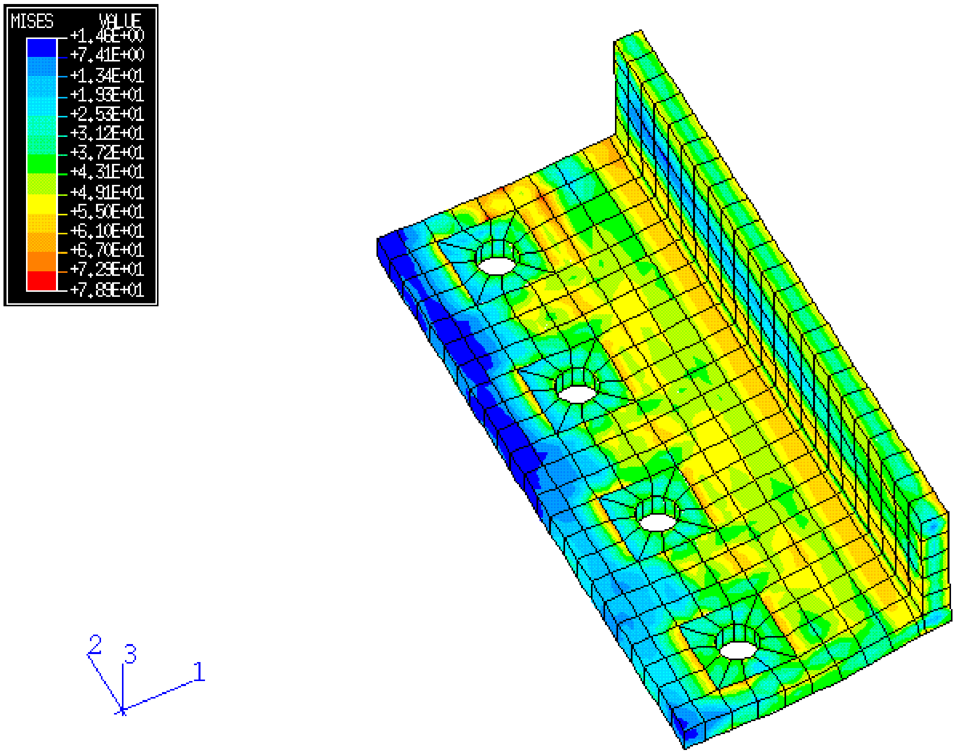


Figure 3.5 Load-Displacement Relationship of the L5x3x1/4 Angle Test



(a) Deformed Shape of an L5x3x1/4 Angle



(b) von Mises Stress Diagram of an L5x3x1/4 Angle

Figure 3.6 Deformed Shape and von Mises Stress Diagram of the 3D FEM L5x3x1/4 Angle at 16.16 kips

Table 3.1 Data for the Load-Displacement Relationship of the 3D FEM L5x3x1/4

Double Angle Connection due to Tension Loading

Loading Stage	Displacement (in.)	Load (kips)
1	0	0
2	0.0131	1.74
3	0.0207	3.23
4	0.032	5.40
5	0.0472	7.91
6	0.0623	9.75
7	0.0777	10.98
8	0.0931	11.54
9	0.109	11.89
10	0.124	12.16
11	0.139	12.41
12	0.155	12.62
13	0.17	12.84
14	0.185	13.03
15	0.201	13.24
16	0.216	13.40
17	0.232	13.55
18	0.247	13.70
19	0.262	13.86
20	0.277	14.00
21	0.293	14.16
22	0.308	14.30
23	0.323	14.46
24	0.338	14.60
25	0.354	14.75
26	0.369	14.89
27	0.384	15.05
28	0.399	15.19
29	0.414	15.34
30	0.43	15.48
31	0.445	15.61
32	0.46	15.76
33	0.475	15.89
34	0.491	16.03
35	0.506	16.16

3.4.2 Coupon Test Using L5x3x1/2 Angles

Since the actual yield stress of the L5x3x1/2 angle specimen was 49.2 ksi., the 3D finite element model was executed again to investigate the load-displacement relationship and the initial stiffness of the angle tested.

Figure 3.7 shows the load-displacement relationship of the L5x3x1/2 double angle connection under axial tensile loads. The load-displacement curve of the experimental test shows a large initial discrepancy with that of the 3D finite element analysis. The initial stiffness is 2,975 kips/in. from the load-displacement curve of the actual test, while that of the 3D finite element analysis is 1,332 kips/in. The load-displacement curve of the experimental test is begins to round out at approximately 15 kips. During the experimental test, yield lines formed along the edge of the washers. Considering the results of this experimental test, the failure of this double angle connection is due to the yielding of the outstanding leg of the angle.

Figure 3.8 shows the deformed shape of the L5x3x1/2 double angle connection and the von Mises stress diagram at the applied load of 53.52 kips from the 3D finite element analysis. The yielding zones formed along the edge of the bolt and the corner of the angle. Table 3.2 contains the data for the load-displacement relationship of the 3D FEM L5x3x1/2 double angle connection under axial tensile loading.

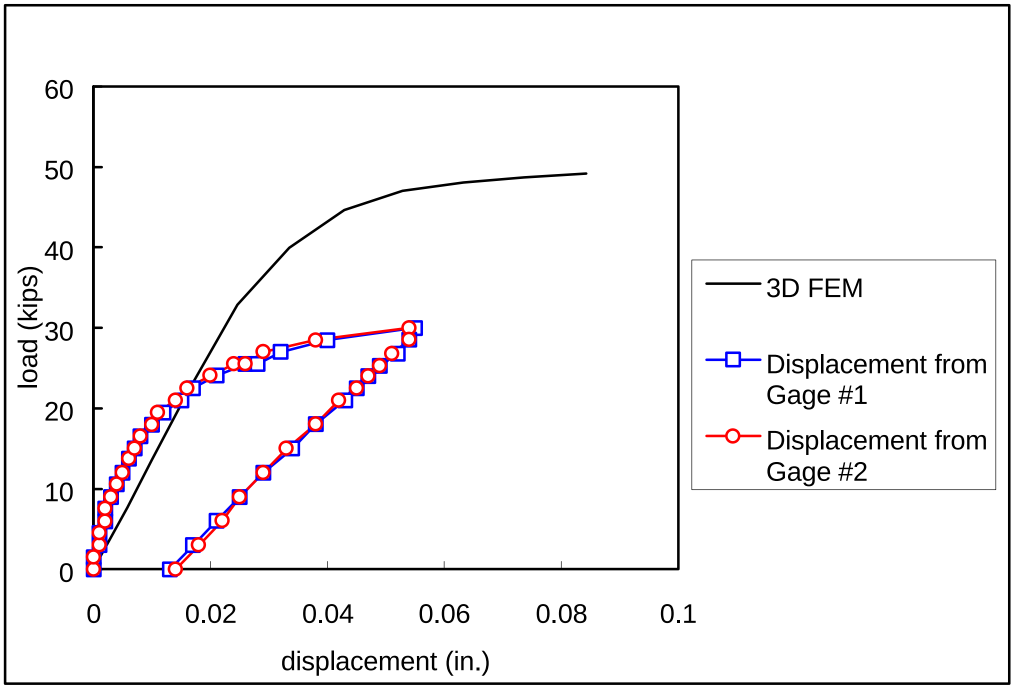
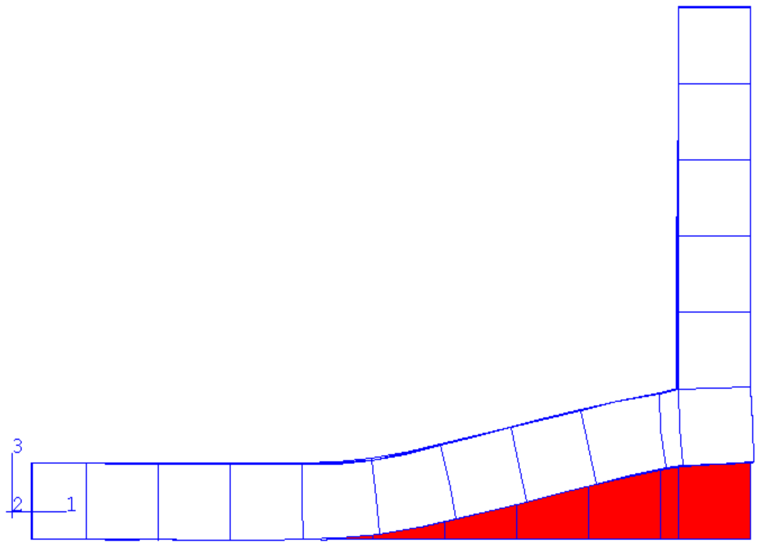
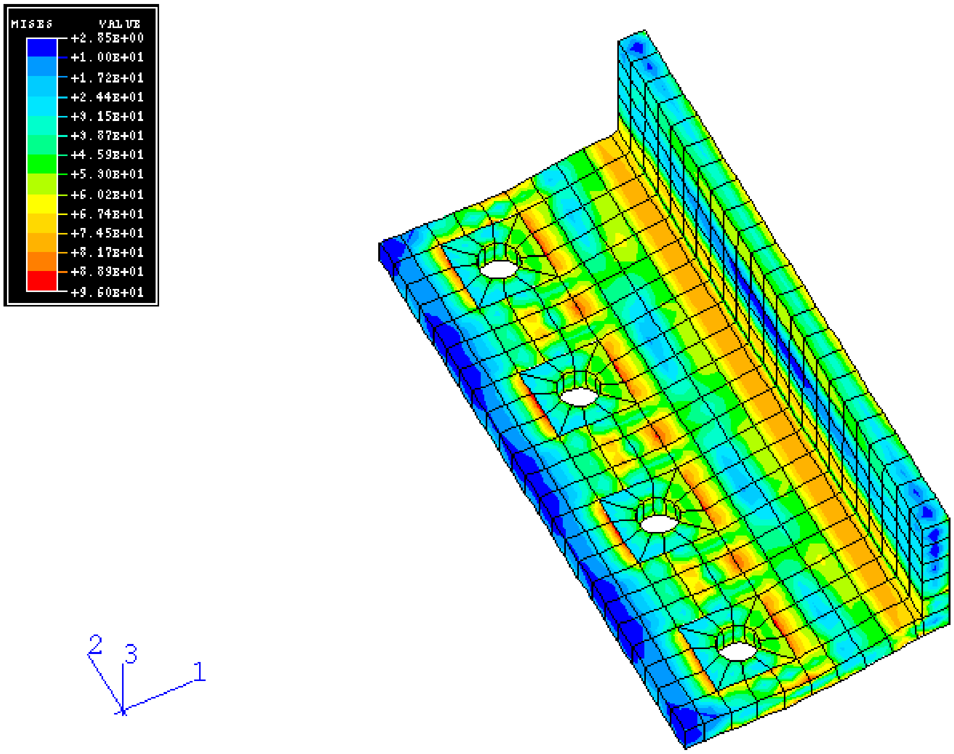


Figure 3.7 Load-Displacement Relationship of the L5x3x1/2 Angle Test



(a) Deformed Shape of an L5x3x1/2 Angle



(b) von Mises Stress Diagram of an L5x3x1/2 Angle

Figure 3.8 Deformed Shape and von Mises Stress Diagram of the 3D FEM

L5x3x1/2 Angle at 53.52 kips

Table 3.2 Data for the Load-Displacement Relationship of the 3D FEM L5x3x1/2 Double Angle Connection due to Tension Loading

Loading Stage	Displacement (in.)	Load (kips)
1	0	0
2	0.00576	7.67
3	0.0099	13.54
4	0.0162	22.12
5	0.0246	32.83
6	0.0335	39.97
7	0.0429	44.66
8	0.0529	47.03
9	0.0632	48.06
10	0.0737	48.68
11	0.0843	49.14
12	0.137	50.57
13	0.189	51.66
14	0.241	52.51
15	0.291	53.00
16	0.34	53.15
17	0.39	53.21
18	0.439	53.28
19	0.487	53.42
20	0.507	53.52

3.5 THORNTON'S FORMULA

The experimental tensile tests were conducted to verify the results of the 3D finite element model. The load-displacement curve and the initial stiffness of the experimental test were compared to those of the 3D finite element analysis. To obtain the approximate initial stiffness of an angle, Thornton (1997) suggested a formula for the calculation of the initial stiffness of an angle as follows:

$$K = El\left(\frac{t}{b}\right)^3 \tag{3.9}$$

where,

t = angle thickness

l = length of the angle

b = the distance between the center of a bolt and the center of a back-to-back angle leg

E = Young's modulus

= 29,000 ksi

Using Thornton's formula, the initial stiffness of the L5x3x1/4 angle can be calculated as follows:

$$\begin{aligned} K &= (29{,}000 \times 11.5)\left(\frac{0.25}{3.475}\right)^3 \\ &= 124.2\ kips/in. \end{aligned} \tag{3.10}$$

Similarly, for the L5x3x1/2 angle,

$$\begin{aligned} K &= (29{,}000 \times 11.5)\left(\frac{0.5}{3.35}\right)^3 \\ &= 1{,}108.8\ kips/in. \end{aligned} \tag{3.11}$$

The initial stiffness of the L5x3x1/4 angle test shows a higher initial stiffness than that of Thornton's formula by 25.5 %, while the initial stiffness of the 3D finite element model shows a higher initial stiffness than that of Thornton's formula by only 7.1 %. For the L5x3x1/2 angle test, the initial stiffness of the 3D finite element model shows a higher initial stiffness than that of Thornton's formula by 16.7 %. However, there is a big discrepancy between the initial stiffness of the 3D finite element model and the initial stiffness of the experimental test. Table 3.3 contains the data for the initial stiffness of the L5x3x1/4 angle and the L5x3x1/2 angle under axial tensile loads.

Table 3.3 Data for the Initial Stiffness of the L5x3x1/4 Angle and the L5x3x1/2 Angle due to Tension Loading

	Experimental Test (kips/in.)	3D Finite Element Model	Thornton's Formula
L5x3x1/4 Angle	166.7	133	124.2
L5x3x1/2 Angle	2975	1331.6	1108.8

From the observation of the experimental test, two inflection points are formed along the outstanding leg of the L5x3x1/4 angle. The location of the first inflection point is 1/4 in. away from the edge of the F436 circular washer, while that of the second one is formed along the fillet of the outstanding leg of the L5x3x1/4 angle. Thus, the distance between these two inflection points is 1.866 in. Since the design strength of the L5x3x1/4 angle is mainly determined by the bending of the outstanding leg as shown in the previous Section 3.3, the design strength of the L5x3x1/4 angle connection should be calculated again using the distance between these two inflection points. The new governing design strength of the L5x3x1/4 angle connection is then calculated as follows:

$$\begin{aligned} & 2M_p - T_u i = 0 \\ & T_u = \frac{2M_p}{i} \\ & \quad = (\frac{11.5 \times 0.25^2}{2 \times 1.866})(48.9) \\ & \quad = 9.4\ kips \end{aligned} \tag{3.12}$$

where,

i = distance between the inflection points

From the load-displacement curve of the 3D finite element model in Figure 3.5, it can be easily shown that the curve is beginning to round out at the applied load of 9.7 kips. Compared to the governing design strength of the L5x3x1/4 angle connection, the 3D finite element model gives a good approximation for the calculation of the design strength.

Similarly, for the L5x3x1/2 angle, the location of the first inflection point is 1/4 in. away from the edge of the F436 circular washer, while that of the second one is formed along the fillet of the outstanding leg. Thus, the distance between these two inflection points is 1.62 in. The new governing strength of the L5x3x1/2 angle connection is calculated as follows:

$$\begin{aligned} &2M_p - T_u i = 0 \\ &T_u = \frac{2M_p}{i} \\ &\quad = (\frac{11.5 \times 0.5^2}{2 \times 1.62})(49.2) \\ &\quad = 43.7\ kips \end{aligned} \tag{3.13}$$

From the load-displacement curve of the 3D finite element model in Figure 3.7, it can be easily shown that the curve is beginning to round out at 40 kips. Compared to the governing design strength of the L5x3x1/2 angle connection, the 3D finite element model gives a good approximation for the calculation of the design strength. However, there is a big discrepancy between the load-displacement curve of the 3D finite element model and that of the experimental test.

3.6 SUMMARY AND CONCLUSIONS

The experimental tests have been conducted to verify the results of the 3D finite element model. The load-displacement curve and the initial stiffness of the experimental test show good agreement with those of the 3D finite element analysis for the L5x3x1/4 angle connection. Considering the results of this experimental test, it is reasonable to accept the 3D finite element model as a good model for the analysis of a double angle connection.

From the observations of the experimental tests, the first inflection point is usually formed at the location of a point which is *t* in. away from the edge of the washer, where *t* is the thickness of the angle which is used in each test. The second inflection point is formed along the fillet of each angle. The distance between these two inflection points plays an important role in the calculation of the design strength of a double angle connection since the bending of the outstanding leg of an angle is usually dominant in the failure of a double angle connection.