

# Block Shear Tests in High-Strength Steel Angles

JEREMY M. GROSS, JAMES G. ORBISON, and RONALD D. ZIEMIAN

## ABSTRACT

Full-scale tests of A588 Grade 50 single-angle tension members, with bolted connections designed to fail in block shear, were conducted. Maximum loads were compared with those predicted by the current American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD) Specifications. It was found that both methods were very accurate in predicting the experimental load capacities. However, the procedure provided in the first edition of the LRFD Specification is shown to consistently, and in some cases significantly, overestimate the nominal failure loads. That procedure is adequate, however, when the resistance factor,  $\phi$ , is applied and design resistance is compared.

## INTRODUCTION

Block shear is a known failure mode in bolted connections for tension members, simple beam connections, and gusset plates. A typical bolted connection for a single angle tension member is shown in Figure 1. A block shear failure of the connection includes shear yield or rupture through the line of bolts parallel to the applied load, and tensile yield or rupture along a plane perpendicular to the load. In some cases, the "block" of material bounded by these two planes may separate completely from the angle; this is the mechanism assumed by the AISC ASD Specification's<sup>1</sup> block shear load capacity procedure. However, block shear load capacities provided in the AISC LRFD Specifications<sup>2,3</sup> are based upon a failure mechanism defined by rupture of one plane only and yield occurring along the other plane.

A previous survey<sup>4</sup> of experimental block shear studies that provide the basis for the AISC methods revealed that most tests to date have been performed on A36 or similar strength steels. Hence, the research<sup>5</sup> reported herein was developed to provide experimental block shear failure data on single angle tension specimens fabricated from higher strength steels. Ten A588 angles fabricated from A588 Grade 50 weathering steel,

and an additional three angles of A36 steel, were tested. They were designed to fail in block shear, and all thirteen specimens exhibited this failure mode. To assess the performance of the AISC design procedures, failure loads obtained in these tests are compared with load capacities predicted by the LRFD and ASD Specifications.

The current LRFD Specification employs a block shear failure load prediction procedure that is based upon two possible failure mechanisms which are primarily a function of the connection geometry. If  $A_{nt}F_u \geq 0.6A_{gv}F_u$ , then the block shear capacity is controlled by rupturing of the tension plane (see Figure 1) and full yielding of the shear plane. The corresponding nominal load capacity is

$$R_n = A_{nt}F_u + 0.6A_{gv}F_y \quad (1)$$

where:

- $A_{nt}$  = Net area subjected to tension
- $A_{gv}$  = Gross area subjected to shear
- $F_u$  = Material ultimate tensile strength
- $F_y$  = Material tensile yield strength
- $R_n$  = Predicted nominal block shear load capacity

When  $A_{nt}F_u < 0.6A_{gv}F_u$ , block shear failure is assumed to occur by rupture of the shear plane and yield of the tension plane. In this case, the nominal capacity is

$$R_n = A_{gv}F_y + 0.6A_{nt}F_u \quad (2)$$

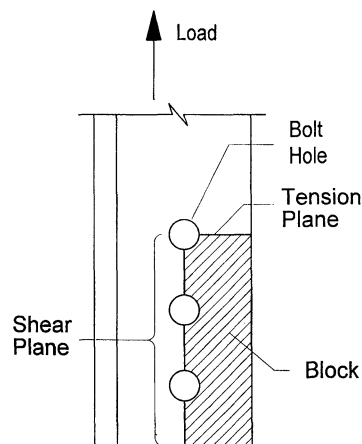


Fig. 1. Typical block shear failure mechanism.

Jeremy M. Gross is structural engineer, Aberjona Engineering, Inc., Winchester, MA.

James G. Orbison, department of civil engineering, Bucknell University, Lewisburg, PA.

Ronald D. Ziemian, department of civil engineering, Bucknell University, Lewisburg, PA.

where:

$A_{gt}$  = Gross area subjected to tension  
 $A_{nv}$  = Net area subjected to shear

The AISC ASD procedure assumes a block shear failure occurs by simultaneous rupture of the net shear and tension planes, and as such may be considered an upper bound on the load capacity. Neglecting a factor of safety of 2.0, the ASD unfactored or nominal load capacity is given by the single equation:

$$R_n = A_n F_u + 0.6 A_{nv} F_u \quad (3)$$

### EXPERIMENTAL PROGRAM

Ten A588 Grade 50 and three A36 steel single angle tension members with various leg sizes and a uniform thickness of 1/4-in. were fabricated with end connections consisting of two or more 3/4-in. diameter A490 bolts in a single bolt line. The angles and their connections were designed such that a block shear failure mode would limit the load capacity. A490 bolts were required in some specimens to ensure that a bolt shear failure would not control, and were used in all specimens for simplicity; threads were excluded from the shear plane in all cases. Bolt holes were drilled to a diameter of 13/16-in., and a bolt hole spacing of 2 1/2-in. was used. Material properties were determined from coupons cut from excess angle lengths during fabrication. In all cases, yield and ultimate tensile strengths significantly exceeded minimum specified values. Specimen numbers and their corresponding connection geometries and material properties are shown in Figure 2 and Table 1.

T-shaped grips were fabricated for the 200,000-lb. capacity universal testing machine used for loading. Lacquer was applied to each specimen end, and the specimens were bolted to 3/4-in. plates, with bolts tightened to a snug-tight condition.

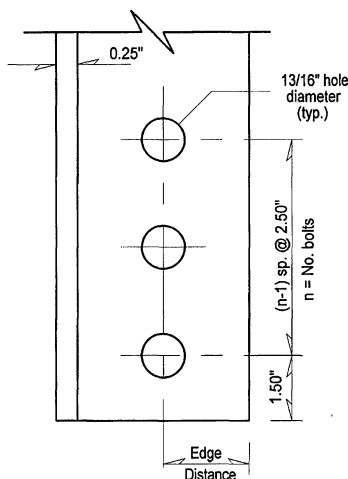


Fig. 2. Connection geometry of single angle specimens.

A typical test arrangement is shown in Figure 3. Load was applied to each specimen at a rate of approximately 8,000 pounds per minute. Maximum loads were recorded, and in all cases elongation was continued well into the unloading region.

### RESULTS

All thirteen specimens failed in block shear. In all tests, the maximum load was limited by a ductile rupture of the tension plane preceded by significant necking. A typical failure, that of specimen A588-5, is shown in Figure 4. At the time of tension plane rupture, yield of the shear plane (primarily along the edge of the bolt holes opposite the "block") was also evident. Expected out-of-plane bending was observed in all tests, and significant in-plane bending developed after the tension plane ruptured. Predicted and actual failure loads are listed in Table 2. In all cases, net tension and shear plane areas were computed using an effective hole diameter of 7/8-in.

In Table 3, a professional factor<sup>6</sup> (defined as the ratio of experimental failure load to predicted failure load) for each equation is provided for all tests. Professional factors less than 1.0 indicate an unconservative load prediction, while factors exceeding 1.0 are produced by conservative predictions. The failure loads predicted by the LRFD and ASD equations, Equations 1, 2 and 3, are computed without incorporating resistance factors or factors of safety.

Based on the current LRFD procedure and the specimen geometries tested herein, Equation 2 governed in all cases. The professional factor mean for this procedure and these tests is 0.96, with a standard deviation of 0.05 and range of 0.89 to 1.07. Note that this accuracy was obtained even though the governing equation, Equation 2, is based on a mechanism defined by rupture of the shear plane and yield of the tension plane, a failure mode which was never observed during any of the tests.

The procedure in the first edition of the LRFD Specifica-

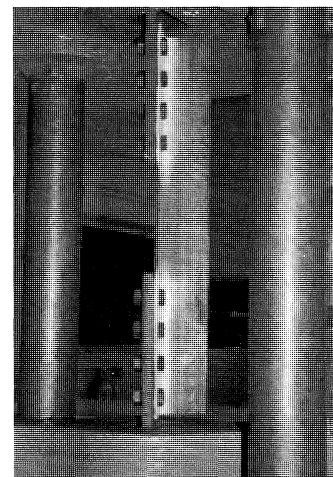


Fig. 3. Typical specimen arrangement for testing.

tion, recommending use of the larger capacity obtained from the two equations, produced significantly different accuracies. This procedure, resulting in Equation 1 governing for all test specimens except A36-1 and A36-2, produced consistently unconservative failure load estimates. Although not shown in Table 3, this procedure and the test data produced a professional factor mean of 0.90, a standard deviation of 0.07, and a range of 0.80 to 1.07. The current LRFD procedure is clearly more accurate with respect to these test results. The ratio of ultimate to yield strengths is reported in Table 2. For the A36 specimens, this ratio has an average of 1.48; for the A588 specimens, the average of this ratio is 1.29.

The ASD equation predicted block shear failure loads in the A588 specimens with slightly more accuracy than the current LRFD procedure; the professional factor mean was 0.99 with a standard deviation of 0.04. The minimum professional factor was 0.93, indicating a load prediction that was unconservative by seven percent. For all tests, the ASD professional factors produced a mean of 0.99, a standard deviation of 0.04, and a range of 0.93 to 1.07.

Plots comparing the predicted nominal and experimental failure loads for the current LRFD and ASD procedures are shown in Figures 5 and 6, respectively. Figure 7 shows a comparison of the LRFD design failure loads, incorporating the resistance factor  $\phi = 0.75$ , and the corresponding experimental loads. Use of the resistance factor produced conservative load predictions in all tests. Figure 8 shows the nominal failure loads predicted by the procedure provided in the first edition of the LRFD Specification.

In all tests, the general mode of failure was rupture at the tension plane and yielding along the shear plane. In each test, the applied load decreased immediately upon rupture of the

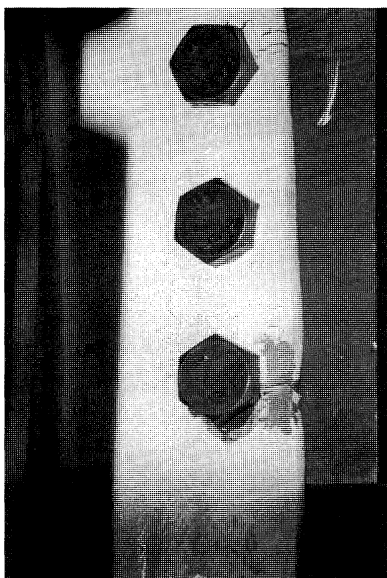


Fig. 4. Specimen A588-5 at maximum load.

tension plane. In all specimens except A588-8, A588-9 and A588-10, the load then remained relatively constant as elongation continued until in-plane bending caused a further, gradual load reduction. With the tension plane ruptured, this constant load was resisted entirely by the shear plane. These loads are shown in Table 4, along with a corresponding shear ultimate strength coefficient,  $C_v$ . This coefficient is computed as:

$$C_v = \frac{R_v}{A_{nv}F_u} \quad (4)$$

where:

- $R_v$  = Load resisted by the shear plane
- $A_{nv}$  = Net area subjected to shear
- $F_u$  = Material ultimate tensile strength

For the test data obtained, the mean shear coefficient after rupture of the tension plane was 0.71. It is interesting to note that both the LRFD and ASD procedures predicted the failure load with good accuracy even though both procedures assume the ultimate material shear strength to be  $0.6A_{nv}F_u$ , indicating a shear coefficient  $C_v$  of 0.60. Specimens A588-8 through A588-10 did not exhibit a near-constant load following rupture of the tension plane, and specimen A588-7 did so only momentarily. These four specimens all used 4-bolt connections, and continued tearing of the specimen at the innermost bolt hole, at an angle from the shear plane, was observed following tension plane rupture. It is possible that this mode of failure was caused by the in-plane rotational restraint

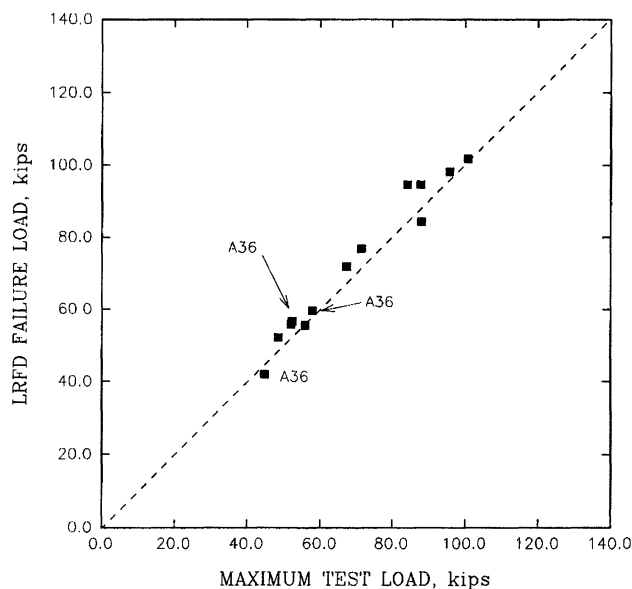


Fig. 5. LRFD predicted failure loads vs. experimental maximum loads.

Specimen	Connected Leg (in.)	Outstanding Leg (in.)	Length Overall (in.)	Number of Bolts (n)	Edge Distance (in.)	Leg Thickness (in.)	Agv (sq. in.)	Anv (sq. in.)	Agt (sq. in.)	Ant (sq. in.)	Yield Strength (ksi)	Ultimate Strength (ksi)
A36-1	3.0	3.0	17.0	2	1.25	0.251	1.00	0.67	0.31	0.20	45.3	68.5
A36-2	4.0	3.0	25.0	3	1.25	0.256	1.66	1.10	0.32	0.21	45.2	68.0
A36-3	4.0	4.0	25.0	3	1.25	0.255	1.66	1.10	0.32	0.21	44.8	64.1
A588-1	4.0	3.0	20.0	2	1.25	0.263	1.05	0.71	0.33	0.21	62.0	83.5
A588-2	4.0	3.0	25.0	3	1.75	0.262	1.70	1.13	0.46	0.34	62.1	82.4
A588-3	4.0	3.0	25.0	3	1.25	0.254	1.65	1.10	0.32	0.21	63.8	86.0
A588-4	4.0	4.0	20.0	2	1.25	0.256	1.02	0.69	0.32	0.21	62.0	78.1
A588-5	4.0	4.0	25.0	3	1.25	0.253	1.64	1.09	0.32	0.21	62.8	79.4
A588-6	4.0	4.0	20.0	2	1.50	0.251	1.00	0.67	0.38	0.27	62.5	79.0
A588-7	4.0	4.0	30.0	4	1.25	0.268	2.41	1.59	0.34	0.22	60.8	77.6
A588-8	4.0	4.0	30.0	4	1.50	0.251	2.26	1.49	0.38	0.27	62.5	79.4
A588-9	4.0	4.0	30.0	4	1.75	0.252	2.27	1.50	0.44	0.33	61.9	79.0
A588-10	4.0	4.0	30.0	4	2.00	0.252	2.27	1.50	0.50	0.39	62.6	78.1

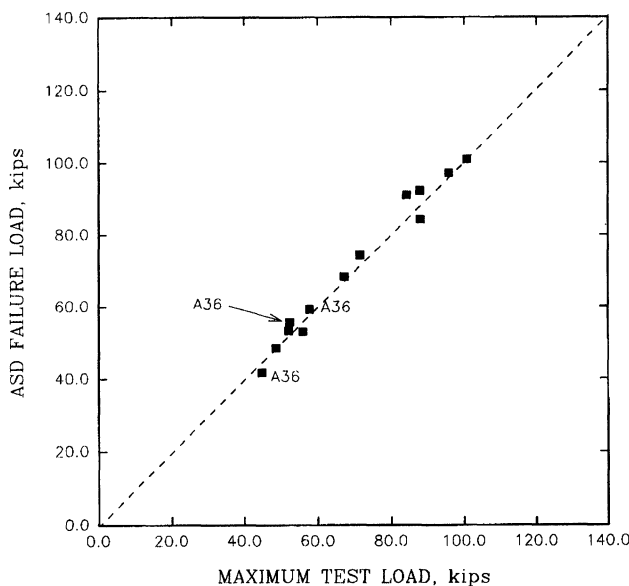
provided by these relatively long bolt lines, which increased the in-plane bending moment at the innermost bolt hole.

### CONCLUSIONS

Ten A588 Grade 50 and three A36 single angle tension members, designed to fail by block shear, were tested to failure. In all cases, block shear failures involving rupture of the tension plane and yield of the shear plane occurred.

It was found that the AISC ASD block shear equation accurately predicted the failure loads in both the A36 and A588 specimens. The current AISC LRFD procedure also produced accurate failure load predictions for both the A36 and A588 specimens tested in this study, although the governing mechanism did not agree with the experimentally observed mechanism. Use of the procedure provided in the first edition of the LRFD Specification consistently, and in some cases significantly, overestimated the failure loads of the A588 specimens.

Finally, it is worth noting that in the current AISC Specifications, the ultimate strength of the shear plane is defined as 60 percent of the ultimate tensile strength of the steel multiplied by the net shear plane area. Based on the test data obtained in this study, it appears that this assumption, which is similar to a von Mises failure criteria where the shear yield strength may be taken as 60 percent of the tensile yield strength, may be inaccurate. It is possible that the critical



*Fig. 6. ASD predicted failure loads vs. experimental maximum loads.*

**Table 2.**  
**Predicted and Actual Failure Loads**

Specimen	Gross Area Yield (kips)	Net Section Rupture (kips)	Bolt Bearing (kips)	Bolt Shear (kips)	LRFD Eq. 1 (kips)	LRFD Eq. 2 (kips)	ASD Eq. (kips)	Maximum Test Load (kips)	$F_u / F_y$
A36-1	58.7	62.7	46.7	49.7	41.3	41.9	41.7	44.8	1.51
A36-2	68.7	84.7	75.1	74.6	59.3	59.5	59.2	57.8	1.50
A36-3	78.2	93.5	70.5	74.6	57.8	56.6	55.6	52.3	1.43
A588-1	94.3	91.4	59.7	49.7	57.0	55.8	53.3	52.0	1.35
A588-2	94.5	102.3	93.1	74.6	91.8	84.3	84.2	88.0	1.33
A588-3	97.0	107.3	94.2	74.6	81.0	76.8	74.3	71.4	1.35
A588-4	108.3	100.5	54.4	49.7	54.3	52.1	48.5	48.5	1.26
A588-5	109.6	116.0	54.6	74.6	78.3	71.8	68.3	67.2	1.26
A588-6	109.1	101.9	53.9	49.7	58.7	55.5	53.0	55.9	1.26
A588-7	106.2	112.5	122.8	99.5	104.9	94.5	91.0	84.2	1.28
A588-8	109.1	116.1	117.7	99.5	105.9	94.5	92.2	87.8	1.27
A588-9	108.1	115.5	117.6	99.5	110.4	98.2	97.1	95.8	1.28
A588-10	109.3	114.2	116.2	99.5	115.9	101.7	100.9	100.8	1.25

Note 1: LRFD Eq. 2 governs in all cases under current AISC Specifications.  
 Note 2: LRFD failure loads are computed without the resistance factor.  
 Note 3: ASD loads are computed assuming a factor of safety of 2.0.

section in shear is not the net section passing through the centerline of the bolt holes, but rather a gross area section located along the edge of the holes opposite the "block."

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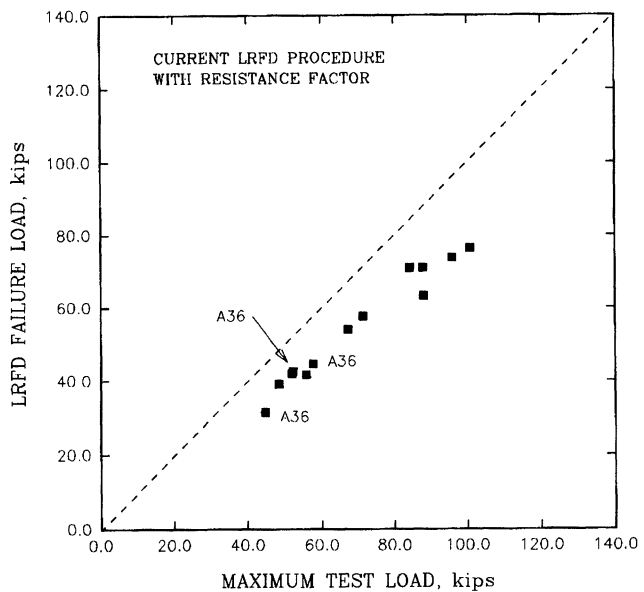


Fig. 7. LRFD predicted loads (with resistance factor) vs. experimental maximum loads.

Table 3. Professional Factors				
Specimen	LRFD Eq. 1	LRFD Eq. 2 (Govern.)	Previous Governing LRFD Eq.	ASD Eq.
A36-1	1.08	<b>1.07</b>	1.07	1.07
A36-2	0.97	<b>0.97</b>	0.97	0.98
A36-3	0.90	<b>0.92</b>	0.90	0.94
A588-1	0.91	<b>0.93</b>	0.91	0.98
A588-2	0.96	<b>1.04</b>	0.96	1.05
A588-3	0.88	<b>0.93</b>	0.88	0.96
A588-4	0.89	<b>0.93</b>	0.89	1.00
A588-5	0.86	<b>0.94</b>	0.86	0.98
A588-6	0.95	<b>1.01</b>	0.95	1.05
A588-7	0.80	<b>0.89</b>	0.80	0.93
A588-8	0.83	<b>0.93</b>	0.83	0.95
A588-9	0.87	<b>0.98</b>	0.87	0.99
A588-10	0.87	<b>0.99</b>	0.87	1.00
<b>All Tests</b> Std. Dev. Maximum Minimum	<b>Mean</b>			
	<b>0.91</b>	<b>0.96</b>	<b>0.90</b>	<b>0.99</b>
	<b>0.07</b>	<b>0.05</b>	<b>0.07</b>	<b>0.04</b>
	<b>1.08</b>	<b>1.07</b>	<b>1.07</b>	<b>1.07</b>
<b>A588 specimens only</b> Std. Dev. Maximum Minimum	<b>Mean</b>			
	<b>0.88</b>	<b>0.96</b>	<b>0.88</b>	<b>0.99</b>
	<b>0.05</b>	<b>0.05</b>	<b>0.05</b>	<b>0.04</b>
	<b>0.96</b>	<b>1.04</b>	<b>0.96</b>	<b>1.05</b>
	<b>0.80</b>	<b>0.89</b>	<b>0.80</b>	<b>0.93</b>

Table 4. Shear Plane Loads and Coefficients After Tension Plane Rupture			
Specimen	Maximum Load (kips)	Shear Plane Load (kips)	Shear Coefficient $C_v$
A36-1	44.8	34.0	0.74
A36-2	57.8	54.0	0.72
A36-3	52.3	48.4	0.69
A588-1	52.0	40.0	0.67
A588-2	88.0	68.0	0.73
A588-3	71.4	67.1	0.71
A588-4	48.5	36.4	0.68
A588-5	67.2	64.2	0.74
A588-6	55.9	39.8	0.75
A588-7	84.2	76.2	0.62
A588-8	87.8	*	*
A588-9	95.8	*	*
A588-10	100.8	*	*
		<b>Mean Std. Dev.</b>	<b>0.71 0.04</b>

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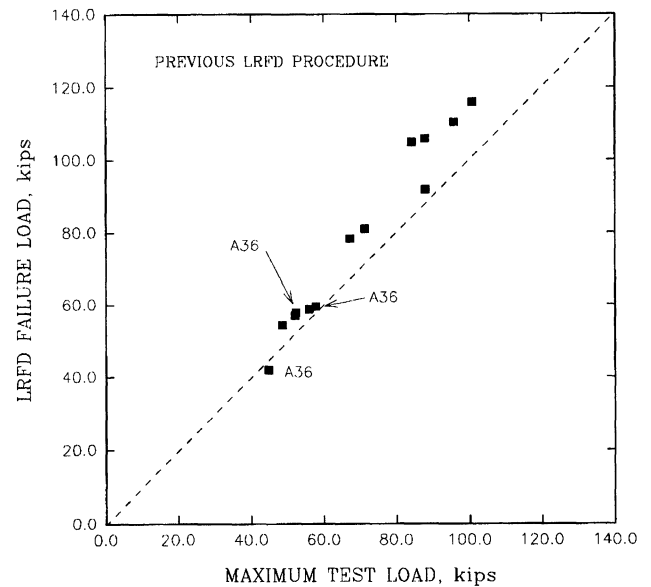


Fig. 8. Previous LRFD procedure predicted loads vs. experimental maximum loads.