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Behaviour and design of structural steel pins

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Abstract. Architectural steel structures with visible tension and compression members are becoming more prevalent as a popular form of construction that reflects the nature of the resistance to the applied loads. These members require the use of structural steel pins at their ends to ensure either axial tension or axial compression in the members. Structural pins have been used as a means of connection for centuries and it would appear that their behaviour is relatively well understood. However, the rules for the design of pins vary quite considerably from code to code and this has caused some confusion amongst consulting structural engineers operating internationally. To provide some insight into this problem, a comprehensive testing program has been carried to examine the influence of parameters such as pin diameter, material properties of the pin, thickness of the loading plates, material properties of the loading plates and the distance of the pin to the edge of the loading plates. The modes of failure have been carefully examined. Based on this study, modifications to current design procedures are proposed that properly take into account the different possible modes of failure.

Key words: bearing; design; failure; pins; shear; steel structures; strength; tests.

1. Introduction

As structural pins have no head and are not threaded, pins cannot carry any axial forces and can only carry shear forces transverse across the pin. Despite this limitation, they are often used in structural applications by designers and architects for steel structures with visible tension and compression members, particularly in applications such as canopies, sporting stadia, convention centres and bridges. In these structural applications, the pins are essentially subjected to static conditions and rotations are generally small.

The design procedures for pins can be found in most structural steel codes, standards and specifications such as Eurocode 3 (CEN 1992), the American AISC-LRFD (AISC 1993), the British BS5950 (BSI 1990) and the Australian AS4100 (SAA 1998). Three of the major design conditions are: shear of the pin; bearing on the pin; and bearing on the plies (plates) that load the pin. While there are similarities between these design codes, there is unexpected significant disparity in some of the design values indicating differences in the design philosophy. For instance, the Australian Standard AS4100 (SAA 1998) has an apparently high design value for the strength of a ply (plate) in bearing and yet a low value for the strength of a pin in shear whereas Eurocode 3 (CEN 1992) has a low value for plate bearing strength but a high value for pin shear strength.

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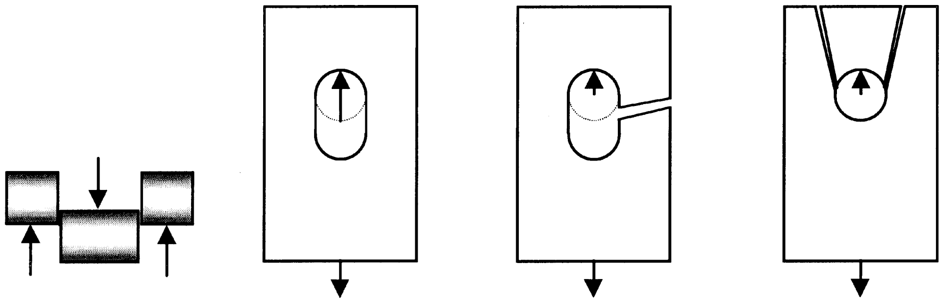

Fig. 1 Typical modes of failures in a single pin connection

To explore this disparity and other effects, the behaviour of structural pins under load has been examined experimentally to determine the effects of the material and geometrical properties of both the pin and the loading plate on the strength and mode of failure of the pin or plate. The results have been compared with design values from steel design codes and standards. Based on the observed behaviour, the design model and the comparisons with codes, modifications to the design procedures have been proposed.

2. Shear and bearing tests

The first series of tests were designed to examine the behaviour of a pinned connection consisting of a snug-fit single pin loaded in double shear by an interior plate between two exterior cover plates. Typical modes of failure for such a connection are shown in Fig. 1.

Each mode of failure was examined by the judicious choice of the variables such as the material properties (yield strength and ultimate tensile strength) of the pin and plates, the diameter of the pin, the thickness of the plates, and the distance of the pin to the edges of the plate. In this series of tests, the edge distance to the plate in the direction of the loading was sufficient to preclude plate end tear-out which is an undesirable mode of failure. To achieve this, the edge distance was kept generally within the design limits of AS 4100 (SAA 1998) for end plate tear-out.

A typical test specimen is shown in Fig. 2. The test pin was located in the upper half of the test specimen. The hole in the top interior test plate was machined to give a snug fit (virtually zero clearance) to the test pin. The two cover plates were designed with sufficient thickness to prevent bearing failures in the cover plates. The lower half of the specimen consisted of a bottom interior plate and two cover plates which were connected using two M20 8.8 bolts having a capacity greater than the pin to ensure failure took place either in the pin or the top interior test plate.

The ends of the top interior test plate and the bottom interior plate were place in the grips of an Avery 580 kN capacity tensile testing machine and tensile load applied to the specimen inducing shear in the pin and bearing in the top interior test plate. The specimens were tested to failure under load control. A displacement controlled tensile testing machine was not available at the time of testing. At each increment of load, the deformation of the interior pin plate relative to the exterior cover plates was measured using dial gauges with a resolution of 0.01 mm and the results were recorded including the final mode of failure.

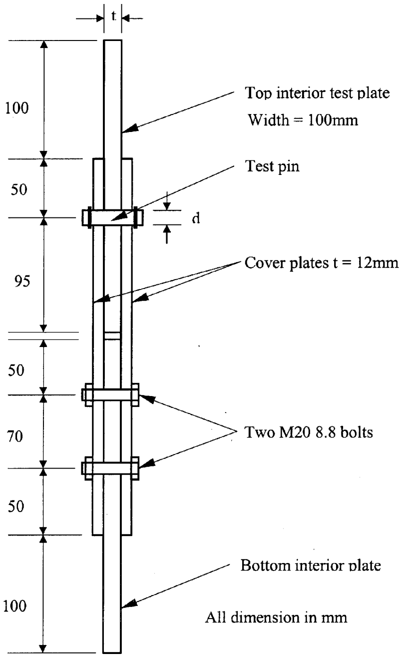

Fig. 2 Test specimen for double shear

The main variables tested were: the diameter d_f of the pin (10, 16 and 27 mm); the thickness t_p of interior test plate (3, 6, 10, 16 and 20 mm); and the material properties of the pin. The pins were cut from two types of commercially available steel rod: black rod with a high ductility and low ratio of yield strength f_{yp} to ultimate tensile strength f_{uf}; and bright rod with a higher 0.2% proof stress f_{yp} and ultimate tensile strength f_{uf} but a lower ductility than the black rod. This was done in order to examine the effect of pin ductility on the behaviour of the pins. Tensile specimens were cut from both the black rod and the bright rod and tested in accordance with Australian Standard AS1391 (SAA 1991). Typical stress-strain curves for the steel in both types of pin are shown in Figure 3. The plate steel had a similar behaviour to the black pin.

Tensile specimens were also cut from each thickness of the interior test plate and tested in accordance with Australian Standard AS1391 (SAA 1991). The shape of the stress-strain curves for the steel plates were similar to that shown in Fig. 3 for the black pin indicating the plates were typical mild steel structural plates. As expected, the yield stress f_{yp} of the plates decreased as the thickness t_p of the plates increased. However, the variation of the ultimate tensile strength f_{up} of the plates with plate thickness was significantly less than the variation of the yield stress f_{yp}.

These tests were conducted by Hayward and van Ommen (1992) at the University of Sydney. The geometrical properties, material properties, test results and modes of failure for the 18 test specimens are shown in Table 1.

The primary mode of failure was either by shearing of the pin (shear deformation of the pin generally being 25% of the pin diameter or greater) or large bearing deformations of the plate (60% of the pin diameter or greater). In some cases, large plate bearing deformations were observed prior to final shearing of the pin. In other cases, fracture of the plate occurred at the cross-section through the pin. These failures have been labelled as secondary modes of failure. No pin bearing failures

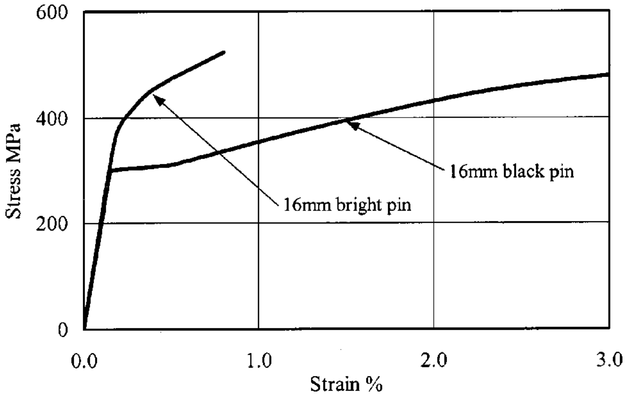

Fig. 3 Stress-strain curves for the two types of pin steel

Table 1 The dimensions, material properties and the test results for the shear and bearing tests

Test No.	Pin d_f mm	Pin f_{yf} MPa	Pin f_{uf} MPa	Plate t_p mm	Plate f_{yp} MPa	Plate f_{up} MPa	Max. Load kN	Primary Failure	Secondary Failure
Black pin tests									
1	10.06	250	455	3.12	360	496	53.6	Pin shear	Plate bearing
2	10.04	250	455	5.97	310	469	54.0	Pin shear	
3	10.06	250	455	9.85	260	485	54.3	Pin shear	
4	16.13	300	499	3.23	360	496	97.0	Plate bearing	
5	16.14	300	499	10.05	260	485	150.8	Pin shear	
6	16.13	300	499	15.86	250	460	146.5	Pin shear	
7	26.95	270	485	3.12	360	496	113.0	Plate bearing	Plate fracture
8	26.95	270	485	9.9	260	485	346.0	Pin shear	Plate bearing
9	26.95	270	485	19.93	250	446	344.0	Pin shear	
Bright Pin Tests									
10	9.97	480	558	3.14	360	496	53.6	Pin shear	Plate bearing
11	10.09	480	558	6.12	310	469	56.8	Pin shear	
12	10.00	480	558	10.11	260	485	56.4	Pin shear	
13	15.97	460	523	3.16	360	496	92.5	Plate bearing	
14	15.97	460	523	9.85	260	485	137.0	Pin shear	
15	15.97	460	523	15.9	250	460	131.0	Pin shear	
16	26.90	450	524	3.12	360	496	110.0	Plate bearing	Plate fracture
17	26.90	450	524	10.17	260	485	352.0	Plate bearing	Plate fracture*
18	26.90	450	524	19.87	250	446	350.0	Pin shear	

*Pin also sheared 25% of diameter

were observed.

The load-deformation curves are shown in Fig. 4 for the ductile 10 mm and 16mm diameter black pins in three different thicknesses of plate. The test specimen with a 10 mm diameter pin in a 3 mm

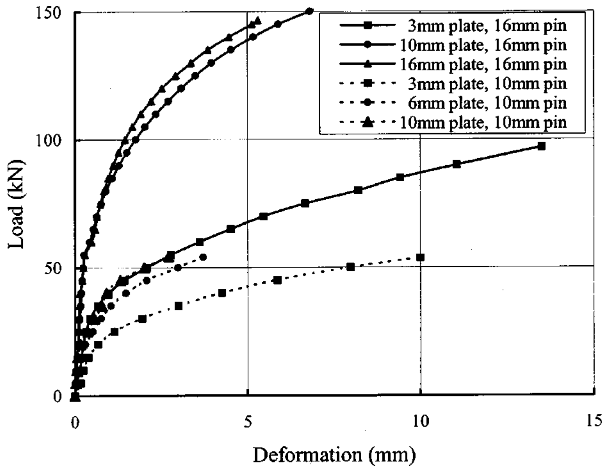

Fig. 4 Load-deformation behaviour for 10 mm and 16 mm diameter black pins

plate and the test specimen with a 16 mm diameter pin in a 3 mm plate both exhibited a primary plate bearing failure. With plate bearing failures, it was observed that hole elongations in excess of 60% of the hole diameter were attained. The other four test specimens shown in Fig. 4 exhibited pin shear failures. For these specimens, it was observed that a shear deformation through the pin itself of 25% of the pin diameter or more was attained prior to failure.

The load-deformation curves are shown in Fig. 5 for the less ductile 10 mm and 16 mm diameter bright pins in three different thicknesses of plate. The 16 mm diameter pin in 3 mm plate exhibited a primary plate bearing failure whereas the 10 mm pin in 3 mm plate exhibited a secondary bearing failure with the primary failure being by pin shear. With these plate bearing failures, it was again observed that hole elongations in excess of 60% of the hole diameter were attained. The other four specimens shown in Fig. 5 exhibited pin shear failures. For these specimens, it was again observed

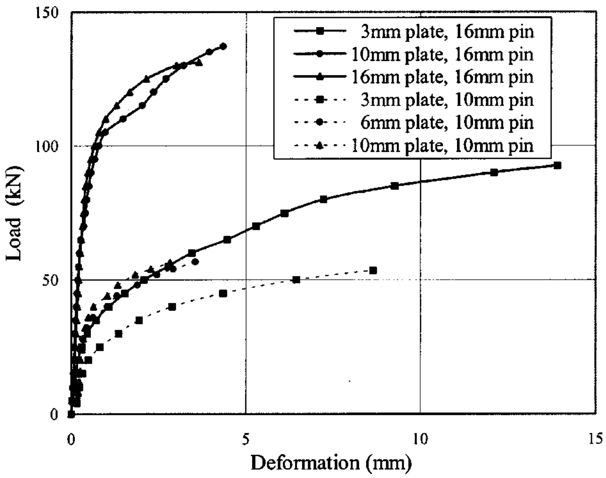

Fig. 5 Load-deformation behaviour for 10 mm and 16 mm diameter bright pins

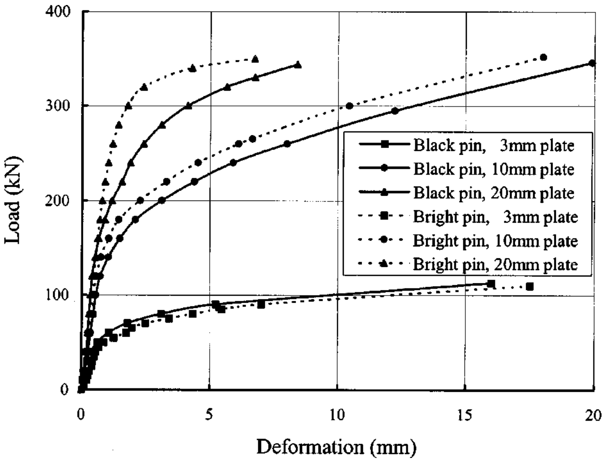

Fig. 6 Load-deformation behaviour for 27 mm diameter black and bright pins

that a shear deformation through the pin itself of 25% of the pin diameter or more was attained prior to failure, even though these pins were manufactured from bright steel with a lower ductility than the black steel.

The load-deformation curves are shown in Fig. 6 for the 27 mm diameter black and bright pins in three different thicknesses of plate. The pins in the 3 mm plate exhibited a primary plate bearing failure followed by plate fracture at large deformations. Again hole elongations in excess of 60% of the hole diameter were attained. The pins in the 10 mm plate were on the borderline between plate bearing failure and pin shear failure. The specimens exhibited large hole elongations followed by pin shear failure for the black pin and plate fracture for the bright pin although the pin shear deformation was also large indicating pin shear failure was close to occurring. The pins in the 20 mm plate exhibited pin shear failures with pin shear deformations through the pin itself of at least 25% of the pin diameter.

3. End tear-out tests

Eye-bars are typically used at the end of pinned tension members. The typical shape of an eye-bar is shown in Fig. 7 together with typical parameters used to define the shape of the eye-bar. Codes such as AS4100 (SAA 1998), BS5950 (BSI 1990) and Eurocode 3 (CEN 1992) require an elongated end on the eye-bar ($D3>D2$) whereas AISC-LRFD (AISC 1993) permits a simpler circular eye bar end ($D3=D2$). The use of an elongated end is aimed at preventing end tear-out failures. However this is at the expense of a more complicated shape to fabricate. Therefore, a series of tests were carried out by Sukkar (1998) to examine whether the simpler circular shape of eye-bar use in the AISC-LRFD (AISC 1993) was adequate in terms of strength.

Simple tension tests were carried out by Sukkar (1998) on flat eye-bars of thickness t_p through which a pin of diameter d_f was placed in similar manner to that shown in Fig. 2. The eye-bars were tested in an Instron 200 kN testing machine under deformation control. The deformation of the pin relative to the eye-bar plate was measured using a LVDT transducer.

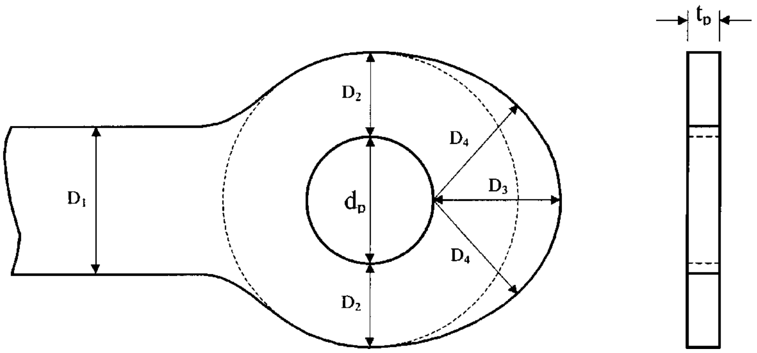

Fig. 7 Typical shape of eye-bars at the end of pinned tension members

The eye-bar dimensions and test results are shown in Table 2. Three plate thicknesses of 5, 6 and 8 mm and two pin diameters of 20 and 27 mm were tested. These dimensions were chosen to ensure possible plate tear-out failures rather than pin shear or plate bearing failures. Tensile specimens were cut from the bright rod used for the pins and tested in accordance with Australian Standard AS1391 (SAA 1991). The stress-strain curve for the pin steel was similar to that shown for the bright pin in Fig. 3. The pin steel had a yield stress f_{yf} (0.2% proof stress) of 730 MPa and an ultimate tensile strength f_{uf} of 870 MPa. Tensile specimens were cut from the plate used for the eyebars and tested in accordance with Australian Standard AS1391 (SAA 1991). The stress-strain curve for the plate steel was similar to that shown for the black pin in Fig. 3. The plate steel had a yield stress f_{yf} of 280 MPa and an ultimate tensile strength f_{uf} of 440 MPa.

Typical load-deformation curves are shown in Fig. 8 for the 20 mm pins and the 27 mm pins in a 6 mm thick eye-bar plate having either a circular or elongated end. It can be seen that the behaviour of the specimens with elongated ends was similar to that of the companion specimens with circular

Table 2 Head type, dimensions and test results for eye-bar specimens

Test No.	Head Type	Pin d_f mm	Plate t_p mm	Eye-bar dimensions $D1$ mm	$D2$ mm	$D3$ mm	Max. Load kN
19	Elongated	20.00	5.0	22.5	15.0	22.5	46.9
20	Circular	20.00	5.0	22.5	15.0	15.0	44.4
21	Elongated	20.00	6.0	22.5	15.0	22.5	52.6
22	Circular	20.00	6.0	22.5	15.0	15.0	47.0
23	Elongated	20.00	8.0	22.5	15.0	22.5	53.6
24	Circular	20.00	8.0	22.5	15.0	15.0	52.7
25	Elongated	27.00	5.0	30.0	20.0	30.0	51.4
26	Circular	27.00	5.0	30.0	20.0	20.0	53.0
27	Elongated	27.00	6.0	30.0	20.0	30.0	54.4
28	Circular	27.00	6.0	30.0	20.0	20.0	54.0
29	Elongated	27.00	8.0	30.0	20.0	30.0	62.2
30	Circular	27.00	8.0	30.0	20.0	20.0	63.1

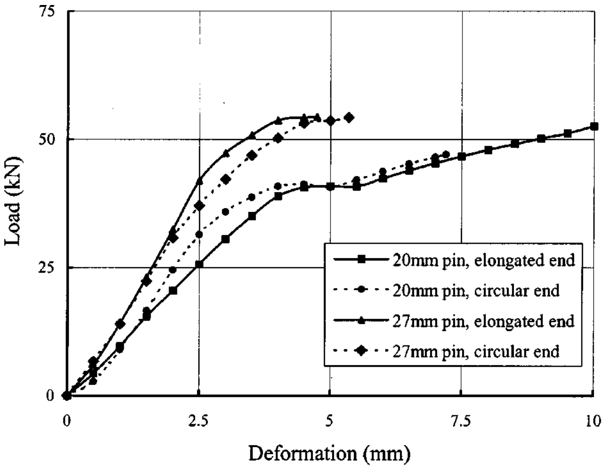

Fig. 8 Typical load-deformation for pins in eye-bars

ends. Unfortunately a final failure was not reached in the tests due to a fault in which the Instron 6027 testing machine was disabled by a frame error under deformation control. Despite this, large deformations up to 50% of the pin diameter were recorded indicating failure was imminent. An examination of the test specimens showed extensive deformation and yielding in shear along the two failure surfaces shown at (d) in Fig. 1 for plate end tear-out failure indicating that this was the likely mode of failure.

4. Comparison with design methods

The typical shape of an eye-bar is shown in Fig. 7 together with the parameters used to define the shape of the eye-bar. The requirements for the dimensions of eye-bars according to Australian (SAA 1998), European (CEN 1992), British (BSI 1990) and American (AISC 1993) practice are listed in Table 3. The possible modes of failure considered by most design codes are shown in Fig. 1. The design strengths for the conditions of pin shear, pin bearing, plate bearing and plate tear-out according to Australian (SAA 1998), European (CEN 1992), British BSI (1990) and American (AISC 1993) practice are shown in Table 4. It can be seen that AS4100 (SAA 1998) is apparently the only code that has a specific check for end tear-out failure. In Table 4, A_f is the cross-sectional area of the pin, d_f is the diameter of the pin, f_{yf} is the yield stress of the steel in the pin, f_{uf} is the

Table 3 Comparison of eye-bar requirements in steel codes and specifications

Steel code	t_p	D_2	D_3	D_4
AS4100 (SAA 1998)	$\geq 0.25\,D_2$	$\geq 0.67\,D_1$	$\geq 1.0\,D_1$	$\geq 1.0\,D_1$
Eurocode 3 (CEN 1992)	n.a.	$\geq 0.75\,d_p$	$\geq 1.1\,d_p$	$\geq 1.1\,d_p$
BS5950 (BSI 1990)	$\geq 0.25\,D_2$	$\geq 0.67\,D_1$	$\geq 1.0\,D_1$	$\geq 1.0\,D_1$
AISC-LRFD (AISC 1993)	$\geq 0.12\,D_1$	$\geq 0.67\,D_1$	$=1.0\,D_2$	n.a.

Table 4 Comparison of design strengths in steel codes and specifications

Steel code	Pin shear	Pin bearing	Plate bearing	Plate tear-out
AS4100 (SAA 1998)	$V_f = 0.62 f_{yf} A_f$	$V_{bf} = 1.4 f_{yf}\, d_f\, t_p$	$V_b = 3.2 f_{up}\, d_f\, t_p$	$V_{bt} = f_{up}\, a_e\, t_p$*
Eurocode 3 (CEN 1992)	$V_f = 0.60 f_{uf} A_f$	$V_{bf} = 1.5 f_{yf}\, d_f\, t_p$	$V_b = 1.5 f_{yp}\, d_f\, t_p$	n.a.
BS5950 (BSI 1990)	$V_f = 0.60 f_{yf} A_f$	$V_{bf} = 1.2 f_{yf}\, d_f\, t_p$	$V_b = 1.2 f_{yp}\, d_f\, t_p$	n.a.
AISC-LRFD (AISC 1993)	$V_f = 0.60 f_{yf} A_f$	$V_{bf} = 1.4 f_{yf}\, d_f\, t_p$	$V_b = 1.4 f_{yp}\, d_f\, t_p$	n.a.

*a_e is the clear distance from the pin to the edge of the plate in the direction of loading

ultimate tensile strength of the steel in the pin, t_p is the thickness of the load-bearing plate, f_{yp} is the yield stress of the steel in the plate, and f_{up} is the ultimate tensile strength of the steel in the plate.

Most code provisions are similar with two major exceptions: Eurocode 3 (CEN 1992) uses the ultimate tensile strength of the pin in calculating the shear strength of the pin (similar to that for bolt strength in most steel codes); and AS4100-1998 uses the ultimate tensile strength of the plate (and a large factor of 3.2) in calculating the bearing strength of the plate. Therefore only AS4100 (SAA 1998) and Eurocode 3 (CEN 1992) are considered in the following comparisons of codes with the test strengths.

The maximum load recorded in each of the tests is compared in Table 5 with the design strengths (assuming a capacity reduction factor of unity) predicted by AS4100 (SAA 1998). For comparison, a load ratio is used in which the maximum load is divided by the design strength for each mode of failure. A load ratio of close to unity indicates close agreement between the design strength and the test strength and a load ratio greater than unity indicates the design strength is conservative. For any given test, the highest value of load ratio defines the mode of failure predicted by AS4100 (SAA 1998) and is marked by an asterisk in Table 5. Therefore the failure mode of pin bearing should have been predicted for test specimens 1, 2, 4, 5, 7, 8, 10, 11, 13, 14, 16 and 17 but this has been ignored as this mode of failure was not observed in the tests. In fact, the load ratios for pin bearing for these specimens were unrealistically high (well in excess of unity) indicating the design model for pin bearing strength is not representative of actual behaviour. This is discussed later when design recommendations are considered.

For test specimens 1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 14, 15 and 18 where the actual primary failure was by pin shear as indicated in Table 1, the strength of the pin in shear predicted by AS4100 (SAA 1998) was markedly lower than the test strengths, particularly for the ductile pins made from black steel rod, as indicated by the high values of Load/V_f well in excess of unity for these specimens. For test specimens 1, 4, 7, 8, 10, 13, 16 and 17 where the primary or secondary failure was by bearing of the plate as indicated in Table 1, the plate bearing strength predicted by AS4100 (SAA 1998) was close to the actual test strengths as indicated by the load ratio Load/V_b being close to unity for these specimens. The bearing strengths predicted for specimens 7, 16, and 17 appear a little high (load ratios less than unity). However the full bearing strength of the plate was not attained in these tests due to premature fracture of the plate adjacent to the hole.

The maximum load recorded in each of the tests is compared in Table 6 with the design strengths (assuming partial material factors of unity) predicted by Eurocode (CEN 1992). For test specimens 1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 14, 15 and 18 where the actual primary failure was by pin shear as indicated in Table 1, the strength of the pin in shear predicted by Eurocode (CEN 1992) was close to the test strengths as indicated by the values of Load/V_f being close to unity for these specimens

Table 5 Comparison of test results with design values predicted by AS4100 (SAA 1998)

Test No.	Max Load (kN)	V_f Pin (kN)	Load/V_f Pin Shear	V_{bf} Pin† (kN)	Load/V_{bf} Pin† Bearing	V_b Plate (kN)	Load/V_b Plate Bearing	V_{bt} Tear-out kN	Load/V_{bt} Plate Tear-out
Pin shear and plate bearing tests									
1	53.6	24.6	2.18*	11.0	4.88	49.8	1.08	139.2	0.38
2	54.0	24.5	2.20*	21.0	2.57	90.0	0.60	251.9	0.21
3	54.3	24.6	2.20*	34.7	1.57	153.8	0.35	429.8	0.13
4	97.0	76.0	1.28*	21.9	4.43	82.7	1.17	139.3	0.70
5	150.8	76.1	1.98*	68.1	2.21	251.7	0.60	423.7	0.36
6	146.5	76.0	1.93*	107.4	1.36	376.6	0.39	634.2	0.23
7	113.0	191.0	0.59	31.8	3.56	133.5	0.85*	126.2	0.90
8	346.0	191.0	1.81*	100.9	3.43	414.1	0.84	391.4	0.88
9	344.0	191.0	1.80*	203.0	1.69	766.6	0.45	724.7	0.47
10	53.6	46.5	1.15*	21.0	2.55	49.7	1.08	140.2	0.38
11	56.8	47.6	1.19*	41.5	1.37	92.7	0.61	258.2	0.22
12	56.4	46.7	1.21*	67.9	0.83	156.9	0.36	441.3	0.13
13	92.5	114.3	0.81	32.5	2.85	80.1	1.15*	136.4	0.68
14	137.0	114.3	1.20*	101.3	1.35	244.1	0.56	415.7	0.33
15	131.0	114.3	1.15*	163.5	0.80	373.8	0.35	636.4	0.21
16	110.0	317.1	0.35	52.9	2.08	133.2	0.83*	126.2	0.87
17	352.0	317.1	1.11*	172.4	2.04	424.6	0.83	402.2	0.88
18	350.0	317.1	1.10*	336.7	1.04	762.8	0.46	722.7	0.48
Eye-bar end tear-out tests									
19	46.9	284.4	0.16	102.2	0.46	140.8	0.33	49.5	0.95*
20	44.4	284.4	0.16	102.2	0.43	140.8	0.32	33.0	1.35*
21	52.6	284.4	0.18	122.6	0.43	169.0	0.31	59.4	0.89*
22	47.0	284.4	0.17	122.6	0.38	169.0	0.28	39.6	1.19*
23	53.6	284.4	0.19	163.5	0.33	225.3	0.24	79.2	0.68*
24	52.7	284.4	0.19	163.5	0.32	225.3	0.23	52.8	1.00*
25	51.4	518.3	0.10	138.0	0.37	190.1	0.27	66.0	0.78*
26	53.0	518.3	0.10	138.0	0.38	190.1	0.28	44.0	1.20*
27	54.4	518.3	0.10	165.6	0.33	228.1	0.24	79.2	0.69*
28	54.0	518.3	0.10	165.6	0.33	228.1	0.24	52.8	1.02*
29	62.2	518.3	0.12	220.8	0.28	304.1	0.20	105.6	0.59*
30	63.1	518.3	0.12	220.8	0.29	304.1	0.21	70.4	0.90*

*Asterisk indicates mode of failure predicted by AS4100 (SAA 1998)
†Pin bearing ignored in predicting failure as none was observed in tests

whereas AS4100 (SAA 1992) was very conservative. For test specimens 1, 4, 7, 8, 10, 13, 16 and 17 where the primary or secondary failure was by bearing of the plate as indicated in Table 1, the plate bearing strength predicted by Eurocode (CEN 1992) was markedly lower than the test strengths as indicated by the high values of load ratio Load/V_b well in excess of unity for these

Table 6 Comparison of test results with design values predicted by Eurocode 3 (CEN 1992)

Test No.	Max Load (kN)	V_f Pin (kN)	Load/V_f Pin Shear	V_{bf} Pin† (kN)	Load/V_{bf} Pin† Bearing	V_b Plate (kN)	Load/V_b Plate Bearing
Pin shear and plate bearing tests							
1	53.6	43.4	1.24	11.8	4.55	17.0	3.16*
2	54.0	43.2	1.25	22.5	2.40	27.9	1.94*
3	54.3	43.4	1.25	37.2	1.46	38.7	1.41*
4	97.0	122.4	0.79	23.4	4.14	28.1	3.45*
5	150.8	122.5	1.23	73.0	2.07	63.3	2.38*
6	146.5	122.4	1.20	115.1	1.27	95.9	1.53*
7	113.0	332.0	0.34	34.1	3.32	45.4	2.49*
8	346.0	332.0	1.04	108.1	3.20	104.1	3.33*
9	344.0	332.0	1.04	217.5	1.58	201.4	1.71*
10	53.6	52.3	1.04	22.5	2.38	16.9	3.17*
11	56.8	53.5	1.06	44.5	1.28	28.7	1.98*
12	56.4	52.6	1.07	72.8	0.77	39.4	1.43*
13	92.5	125.7	0.74	34.8	2.66	27.3	3.39*
14	137.0	125.7	1.09	108.5	1.26	61.4	2.23*
15	131.0	125.7	1.04	175.2	0.75	95.2	1.38*
16	110.0	357.4	0.31	56.7	1.94	45.3	2.43*
17	352.0	357.4	0.98	184.7	1.91	106.7	3.30*
18	350.0	357.4	0.98	360.8	0.97	200.4	1.75*

*Asterisk indicates mode of failure predicted by Eurocode 3 (CEN 1992)
†Pin bearing ignored in predicting failure as none was observed in tests

specimens whereas ASA4100 (SAA 1992) gave good agreement.

For the eye-bars where plate tear-out was both the predicted and the actual mode of failure, AS4100 (SAA 1998) provided a reasonable estimate of the test strength taking the edge distance $a_3 = D3$ and where the design end tear-out strength V_{bt} is given by

$$V_{bt}=3.2f_{up}a_e t_p \tag{1}$$

However, it is interesting to note that the elongation of the eye-bar as used by AS4100 (SAA 1998), BS5950 (BSI 1990) and Eurocode (CEN 1992) did little to improve the actual test strength over that for a simple circular eye-bar and its use should be questioned.

5. Design recommendations

From the comparisons of the test results with the design strengths in AS4100 (SAA 1998) and Eurocode 3 (CEN 1992), it was clear that AS4100 (SAA 1998) provided the best model for plate bearing strength based on the ultimate strength of the steel in the plate whereas Eurocode 3 (CEN 1992) provided the best model for the pin shear strength, again based on the ultimate strength of the steel in the pin. It is therefore proposed that the design strength V_f of a pin in shear should be given by

$$V_f = 0.62 f_{uf} A_f \tag{2}$$

This is similar to the strength of a bolt in shear as given in AS4100 (SAA 1998). The shear factor of 0.62 on the ultimate tensile strength is used to give the shear strength of the steel in the pin. In the tests, the mean value of this factor for the ductile black steel pins was 0.71 with a coefficient of variation of 0.08 with factors ranging from 0.74 for the 10 mm diameter pins to 0.62 for the larger 27 mm diameter pins. For the lower ductility bright steel pins, the mean value of the factor was 0.63 with a coefficient of variation of 0.03 with factors ranging from 0.65 for the 10 mm diameter pins to 0.59 for the larger diameter 27 mm pins.

It is also proposed that the design strength of the plate in bearing should be given by

$$V_b = 3.2 f_{up} d_f t_p \tag{3}$$

This is identical to the current requirements in AS4100 (SAA 1998) for both pins and bolts. The bearing factor of 3.2 on the ultimate tensile strength is used to give the bearing strength of the steel in the plate subjected to loading by a circular pin. In the two tests that had primary bearing failures without plate fracture, the mean value of the factor was 3.74. In the other three bearing failure tests where premature plate fracture occurred, the mean value of this factor was still 2.67, a value close to 3.2.

It is proposed that a new serviceability condition for plate bearing be included in design codes. As shown in Fig. 4 and 5 for the 3 mm plate that failed in bearing, the bearing deformations (hole elongations) of the plate at maximum load are very large and typically exceed 60% of the hole diameter. Using a proof load V_s from the tests that corresponds to a deformation (hole elongation) of 2% of the hole diameter as the basis to define the maximum service bearing load V_{bs} that can be sustained prior to the onset of large plate bearing deformations, a mean design value of bearing strength V_{bs} for serviceability load conditions has been determined as

$$V_{bs} = 1.6 f_{yp} d_f t_p \tag{4}$$

The value of the factor 1.6 was derived from the eight tests that had primary and secondary bearing failures. It is interesting to note that the factor of 1.6 is close to the values for the factors shown in Table 4 for Eurocode 3 (CEN 1992), BS5950 (BSI 1990) and AISC-LRFD (AISC 1993) for plate bearing strengths V_b under ultimate load conditions. It is suggested these three codes are actually applying a serviceability condition for plate bearing (hole elongation) but incorrectly using the design check for forces on the plate at ultimate loads rather than at serviceability loads.

Comparisons of the three design proposals with the test results are given in Table 7 and values of the load ratio are shown for both primary and secondary failure modes. The load ratios are generally close to unity and indicate reasonable agreement over the range of test parameters.

6. Conclusions

A series of tests have been conducted on pin connections using a range of geometrical and material properties for the pin and the loading plate. The parameters used in the tests were such that a number of different failure modes were observed including: shear of the pin; bearing of the plate (hole elongation); plate fracture at the section adjacent to the pin; and end tear-out of the

Table 7 Comparison of test results with design values predicted by modifications to codes

Test	Max Load (kN)	V_f or V_b (kN)	Load / V_f Pin Shear	Load / V_b Plate Bearing	Predicted Failure	Service Load V_s kN	V_{bs} Plate kN	V_s / V_{bs}
1	53.6	44.8	1.20	1.08	Pin shear*	20	18.1	1.11
2	54.0	44.7	1.21		Pin shear			
3	54.3	44.8	1.21		Pin shear			
4	97.0	82.7		1.17	Plate bearing	30	30.0	1.00
5	150.8	126.6	1.19		Pin shear			
6	146.5	126.4	1.16		Pin shear			
7	113.0	133.5		0.85	Plate bearing	38	48.4	0.78
8	346.0	343.1	1.01	0.84	Pin shear*	125	111.0	1.13
9	344.0	343.1	1.00		Pin shear			
10	53.6	54.0	0.99	1.08	Pin shear*	20	18.0	1.11
11	56.8	55.3	1.03		Pin shear			
12	56.4	54.3	1.04		Pin shear			
13	92.5	80.1		1.15	Plate bearing	29	29.1	1.00
14	137.0	129.9	1.05		Pin shear			
15	131.0	129.9	1.01		Pin shear			
16	110.0	133.2		0.83	Plate bearing	42	48.3	0.87
17	352.0	424.6	0.95	0.83	Plate bearing†	130	113.8	1.14
18	350.0	369.3	0.95		Pin shear			

*Plate bearing was a secondary failure mode in the tests
†Pin shear was a secondary failure mode in the tests

plate. Bearing failures of the pin could not be identified nor were they observed even though the design models indicated that they should have occurred for some of the parameters tested.

The tests have highlighted some deficiencies in current codes that are used to predict the strength of structural pins in steel structures. It has been found that the strength of a pin in shear is related to the ultimate tensile strength of the steel used in the manufacture of the pin. The strength of the plate in bearing was also related to the ultimate tensile strength of the steel used for the plate, and bearing stresses over three times the ultimate tensile strength of the plate could be sustained. Most of the codes underestimated the shear strength of the pin and the bearing strength of the plate. The design model in Eurocode 3 (CEN 1992) gave the best prediction for the pin shear strength and the design model in AS4100 (SAA 1998) gave the best prediction for the plate bearing strength.

Modifications have been proposed to the design strengths in the codes that better model the modes of failure. These cover the strength of the pin in shear, the strength of the plate in bearing, and the strength of the plate in end tear-out. A new serviceability condition is proposed for plate bearing. This limits the elongation of the hole in bearing to 2% of the pin hole diameter under service loads.

Plate end tear-out is a mode of failure that should be checked and the design provisions in AS4100 (SAA 1998) give a reasonable estimate of the strength. For eye bars, elongated ends as used by AS4100 (SAA 1998), BS5950 (BSI 1990) and Eurocode (CEN 1992) did little to improve the actual strength over that for a simple circular eye-bar as used by AISC-LRFD (AISC 1993).

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