Bearing capacities and modes of failure in single-bolt lap joints

A R Kemp

Premature failures have been observed to occur in single-bolt lap joints in bearing, particularly where the connected plates are relatively thin and washers are not provided. A series of 28 tests conducted under the author's supervision, as well as 12 tests conducted in Australia, are described covering a range of bolt diameters, plate thicknesses and washer arrangements. In many of these specimens the mode of bearing failure involves rotation and pull-through of the bolt associated with eccentricity of the lap joint. The bearing capacity of many of these joints was found to be well below the strength predicted for conventional bearing failure in the Canadian/South African design code, although within the range predicted in the clause for screws or hollow rivets in lap joints. Revised design criteria are proposed in which the presence of standard or large washers is important in achieving adequate bearing resistance.

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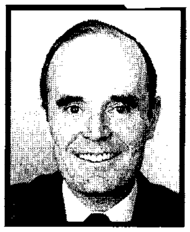

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He has served as Head of Department of Civil Engineering for eight years and Dean of the Faculty of Engineering for four years. He was a Deputy Vice-Chancellor of the university between 1994 and 1998 and Vice-Principal in 1997/98. In 1991 he was President of the SA Institution of Civil Engineering. He has published over 80 papers in the field of structural engineering and is currently Highveld Steel Professor of Civil Engineering (Structural Engineering) in the Civil Engineering Department at the University of the Witwatersrand.

His main research interests are ultimate load analysis and design, ductility, steel and composite design, and loading codes. He has presented invited seminars at the universities of Alberta, British Columbia, Cambridge, Cornell, Edinburgh, Imperial College, Lausanne, Minneapolis and Trento, as well as the Steel Construction Institute (UK). In 2001 he was elected an honorary fellow of the Institution.

Symbols

a	end distance from centre of hole to end of plate
B_r	bearing failure load
C	coefficient in bearing equation
d	nominal diameter of bolt
d_h	diameter of hole
f_u	tensile strength of plate
t	thickness of plate
T_r	tension failure load of net section
w	width of plate
V_r	shear failure load through end pull-out

INTRODUCTION

This research originated from observations that the bearing capacity of bolts on thin, flat, or corrugated plates in single shear is over-estimated in current design codes of practice. Furthermore, bearing failures develop in lap joints in thin plate not only through normally expected elongation of the hole, but more commonly due to rotation of the bolt and eventual pulling of the bolt through the bolt hole in the plate, as shown in figure 1a, associated with eccentricity in the lap joint.

A series of 28 tests was therefore conducted to observe bearing failures in specimens with ratios of bolt diameter to plate thickness in the range of 4 to 12,5. These tests complement observations by Rogers and Hancock (1998a) on specimens with this ratio in the range 20,7 to 29,3, which are included in the evaluations in this paper.

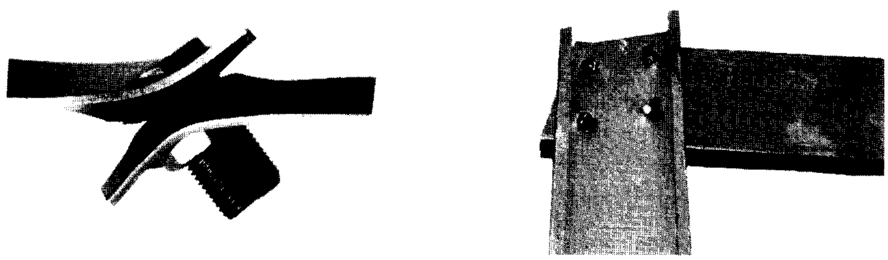
The particular application of these results is for bolting cold-formed channel sections back-to-back in joints in bearing. Preliminary tests had indicated that rotation and pull-through of the bolts occur in such connections, as shown in figure 1b.

DESCRIPTION OF TESTS

Twenty-eight single-bolt bearing tests are reported for the first time in this paper and are referred to as the Kemp series. The following ratios or properties are varied in these tests within the ranges indicated:

- bolt diameter to plate thickness ratio in the range 4,0 to 12,5
- end distance to bolt diameter ratio in the range 2,4 to 4,0
- no washer (NW), standard washer (SW) or large washer (LW) below the nut and under the head of the bolt
- Grade 4.8 bolts varying from 12 mm to 20 mm diameter, with threads up to the head of the bolt

The typical specimen is illustrated in figure 2. The diameter of the punched hole, d_h, in the Grade 300W plate is 2 mm larger than the bolt diameter. The end distance, a, from the centre of the hole to the end of the plate and the net width of plate are sufficiently large to avoid failure in most tests in either shear through the end of the plate or tension across the net section. The direction in which the tension force was applied and the



(a) Lap joint; *(b) Bearing connection*
Figure 1 Pull-through bearing failure

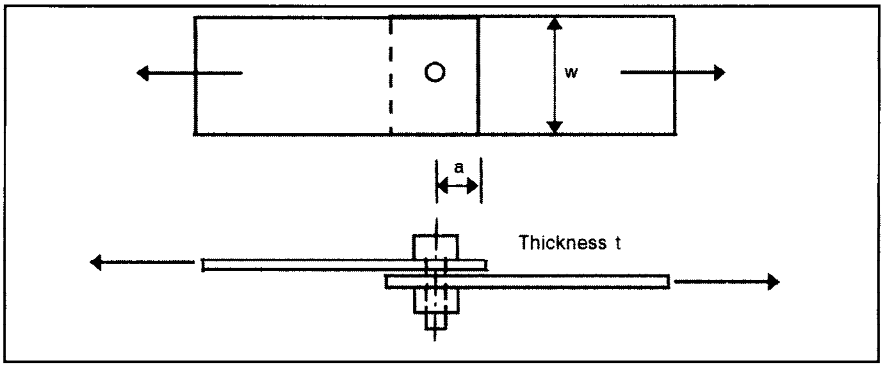


Figure 2 Typical single-bolt lap joints

ultimate stress was derived from coupon tests is parallel to the direction of rolling of the plate.

In addition, 12 single-bolt bearing tests were selected, as the Rogers series, from the extensive series of measurements conducted by Rogers and Hancock (1998a), to complement the tests reported in the Kemp series. The Rogers series were conducted on Grade 300 and Grade 550 plate material in the direction of rolling, possessing a measured ultimate stress in the range 411 to 703 MPa. The bolts were 12 mm diameter, Grade 8.8 and were used with integral (IW) or standard (SW) washers under the nut and bolt. An end distance to the centre of the bolt hole of at least three bolt diameters was provided. These tests illustrate the effects of high yield strength plate material and ratios of bolt diameter to plate thickness in the range 20,3 to 29,3. The bolt holes were 2,3 mm larger than the bolt diameter.

The Rogers series also differed from the Kemp series in that the end of each plate was clipped to its partner in the lapped connection to restrict curling of the plate associated with rotation and pull-through of the bolt. This curling was not restricted in the Kemp series because it had been observed to occur in the back-to-back end connections of channels which were tested separately (see figure 1b). Rogers and Hancock (1998b) also tested specimens in which out-of-plane curling was limited by providing side lips to the plates (referred to as winged specimens).

The most important properties in the Kemp series K1 to K28 and the Rogers series R1 to R12 are summarised in table 1, including the ultimate stress derived from standard coupon specimens of the plate material. The tests are grouped in accordance with the type of washer which is used between the nut and the plate and between the head of the bolt and the plate. These washers are shown in this paper to be important in inhibiting pull-through failures. The type of washer is described as NW where no washers are used, SW where standard-size washers are used (24 x 14 x 1,6 for 12 mm diameter bolt, 30 x 18 x 2,0 for 16 mm diameter bolt and 37 x 22 x 2,0 for 20 mm diameter bolt), LW where large washers are used (30 x 14 x 2,0 for 12 mm diameter bolt, 42 x 18 x 3,0 for 16 mm diameter bolt and 48 x 22 x 3,0 for 20 mm bolt) and IW where a bolt and nut assembly with integral washers of 29,5 mm overall diameter is used in the Rogers series with 12 mm diameter bolts.

DESIGN CODES

Rogers and Hancock (1998b) found that the Canadian code CSA-S136 (Canadian Standards Association 1994) for cold-formed structural steel members is the only design standard which adequately predicts the modes of failure in their extensive series of tests. In fact, the Canadian code correctly predicts the mode of failure in 170 out of 176 of their tests, whereas the success rate with Eurocode 3 (European Committee for Standardisation 1996) is 149 out of 176 and with the Australian/New Zealand code (Standards Australia/Standards New Zealand 1996) is 92 out of 176.

This Canadian code forms the basis of the South African design code for cold-formed steel sections (South African Bureau of Standards 1993) and will

Table 1 Properties of test specimens, Kemp series K1 to K28 and Rogers series R1 to R12

Test reference	Bolt diameter d (mm)	Type of washer*	Plate thickness t (mm)	Width of plate w (mm)	End distance a (mm)	Ultimate stress f_u (MPa)
K1	20	NW	1,60	64	48	387
K2	16	NW	1,60	64	48	387
K3	12	NW	1,60	64	48	387
K4	20	NW	3,03	64	48	389
K5	16	NW	2,46	64	48	410
K6	16	NW	2,46	64	48	410
K7	16	NW	2,87	64	48	461
K8	16	NW	3,03	64	48	389
K9	12	NW	3,03	64	48	389
K10	20	SW	1,60	64	48	387
K11	16	SW	1,60	64	48	387
K12	12	SW	1,60	64	48	387
K13	16	SW	2,10	64	48	380
K14	20	SW	3,03	64	48	389
K15	16	SW	2,46	64	48	410
K16	16	SW	2,46	64	48	410
K17	16	SW	2,87	64	48	461
K18	16	SW	3,03	64	48	389
K19	12	SW	3,03	64	48	389
K20	20	LW	1,60	64	48	387
K21	16	LW	1,60	64	48	387
K22	12	LW	1,60	64	48	387
K23	20	LW	3,03	64	48	389
K24	16	LW	2,46	64	48	410
K25	16	LW	2,46	64	48	410
K26	16	LW	2,87	64	48	461
K27	16	LW	3,03	64	48	389
K28	12	LW	3,03	64	48	389
R1	12	SW	0,41	75	36	703
R2	12	SW	0,41	75	48	703
R3	12	SW	0,41	75	60	703
R4	12	IW	0,41	75	36	703
R5	12	IW	0,41	75	48	703
R6	12	IW	0,41	75	60	703
R7	12	IW	0,58	75	36	411
R8	12	IW	0,58	75	48	411
R9	12	IW	0,58	75	60	411
R10	12	IW	0,59	75	36	686
R11	12	IW	0,59	75	48	686
R12	12	IW	0,59	75	60	686

*Type of washer: NW = no washer; SW = standard washer; LW = large washer; IW = integral washer.

therefore be used for assessing the tests results. In this code, the failure loads for the limit states most relevant to bearing behaviour are as follows, with the resistance factor equal to 1,0 for comparison with the test results:

Mode 1: Bearing failure of hole in plate:

$$B_r = Ctdf_u \qquad (1a)$$

in which t is the plate thickness, d is the diameter of the bolt and f_u is the tensile strength of the plate. The factor C is defined as follows:

$$\begin{aligned} &{}^{d}/_{t} \leq 10 : \; C = 3 \\ &10 < {}^{d}/_{t} \leq 15 : C = 30({}^{t}/_{d}) \\ &{}^{d}/_{t} > 15 : \; C = 2 \end{aligned} \qquad (1b)$$

Although it is indicated in the cold-formed code that a washer 'should' be used under the element that is turned during installation, there is no requirement to provide washers and no reference to washers under both the nut and the head of the bolt.

Mode 2: Rotation of bolt and pull-through bearing failure:

This mode is not referred to specifically in the code. Uncertainty exists about whether clause 7.3.5.3 of the code, which refers to 'simple lap joints in sheets subject to tension connected by screws or hollow rivets', refers to bolts and nuts where the thread extends over the whole length of the bolt shank. The effect of this clause for plates of equal thickness is to reduce the value of C in equation 1b by 50%. Most designers would not make this interpretation and would use equations 1a and 1b for determining the bearing capacity with the appropriate resistance factor. There is no reference to washers in this clause which are shown subsequently to be a critical issue. Rogers does not refer to this clause at all or the associated reduction in strength.

Because of this confusion the test resistances are normalised by dividing the observed ultimate load by the bearing resistance given by equation 1 with C = 3. The normalised resistance therefore represents the extent to which the C-factor falls below a value of 3,0 as the test variables are changed.

Mode 3: Shear failure through end pull-out in plate:

$$V_r = 0{,}6t(2{,}0a - d_h)f_u \qquad (2)$$

in which a is the end distance from the centre of the hole to the end of the plate and d_h is the diameter of the hole.

Mode 4: Tension failure of net section for drilled holes:

$$T_r = 0{,}85(w - d_h)tf_u \qquad (3)$$

in which w is the width of plate

The measured failure load, extension of the specimen, mode of failure (as described above) and comparisons with the predicted failure load and mode of failure based on the above equations are summarised in table 2. For a particular type of washer the tests are listed in reducing order of the ratio of bolt diameter to plate thickness.

Table 2 Test results grouped according to washer type (defined in table 1)

				Test results at failure		Normalised failure load and (mode)	
Type of washer	Test reference	d/t	a/d	Load (kN)	Extension (mm)	Actual mode	Predicted mode for minimum load
NW	K1	12,5	2,4	18,4	17,2	0,49 (2)	0,83 (4)
NW	K2	10,0	3,0	16,1	12,3	0,54 (2)	0,66 (4)
NW	K3	7,5	4,0	11,4	9,4	0,51 (2)	0,51 (1)
NW	K4	6,6	2,4	34,0	10,4	0,48 (2)	0,81 (4)
NW	K5	6,5	2,5	33,1	3,9	0,68 (2)	0,88 (3)
NW	K6	6,5	3,0	33,0	5,8	0,68 (2)	0,84 (4)
NW	K7	5,6	3,0	34,3	12,1	0,54 (2)	0,84 (4)
NW	K8	5,3	3,0	29,1	17,4	0,51 (2)	0,63 (4)
NW	K9	4,0	4,0	28,6	8,2	0,67 (2)	0,67 (1)
SW	K10	12,5	2,4	22,2	21,9	1,01 (4)	1,01 (4)
SW	K11	10,0	3,0	20,7	25,4	0,70 (2)	0,86 (4)
SW	K12	7,5	4,0	16,2	16,5	0,73 (2)	0,73 (1)
SW	K13	7,6	3,0	30,8	20,8	0,80 (2)	0,99 (4)
SW	K14	6,6	2,4	39,8	23,7	0,56 (1)	0,95 (4)
SW	K15	6,5	2,5	43,0	16,6	0,89 (2)	1,15 (3)
SW	K16	6,5	3,0	42,2	16,4	0,87 (2)	1,07 (4)
SW	K17	5,6	3,0	44,3	20,4	0,70 (2)	0,86 (4)
SW	K18	5,3	3,0	36,5	30,1	0,65 (2)	0,79 (4)
SW	K19	4,0	4,0	28,7	7,8	1,41 (5*)	N/A
LW	K20	12,5	2,4	24,8	10,1	1,12 (4)	1,12 (4)
LW	K21	10,0	3,0	29,5	17,4	1,22 (4)	1,22 (4)
LW	K22	7,5	4,0	24,9	28,1	1,12 (2)	1,12 (1)
LW	K23	6,6	2,4	49,0	21,4	1,16 (4)	1,16 (4)
LW	K24	6,5	2,5	47,5	21,5	1,20 (4)	1,27 (3)
LW	K25	6,5	3,0	45,0	20,1	1,14 (4)	1,14 (4)
LW	K26	5,6	3,0	53,5	17,6	1,03 (4)	1,03 (4)
LW	K27	5,3	3,0	52,0	30,0	0,92 (1)	1,13 (4)
LW	K28	4,0	4,0	27,6	9,8	1,36 (5*)	N/A
SW	R1	29,3	3,0	6,0	13,0	0,58 (1)	0,60 (3)
SW	R2	29,3	4,0	7,3	16,7	0,70 (1)	0,70 (1)
SW	R3	29,3	5,0	6,6	9,5	0,64 (1)	0,64 (1)
IW	R4	29,3	3,0	7,4	12,7	0,71 (1)	0,74 (3)
IW	R5	29,3	4,0	7,8	12,2	0,75 (1)	0,75 (1)
IW	R6	29,3	5,0	7,4	10,1	0,72 (1)	0,72 (1)
IW	R7	20,7	3,0	6,2	14,1	0,72 (1)	0,75 (3)
IW	R8	20,7	4,0	6,4	14,0	0,74 (1)	0,74 (1)
IW	R9	20,7	5,0	6,4	14,3	0,74 (1)	0,74 (1)
IW	R10	20,3	3,0	10,0	14,4	0,69 (1)	0,71 (3)
IW	R11	20,3	4,0	9,8	13,0	0,67 (1)	0,67 (1)
IW	R12	20,3	5,0	11,1	18,7	0,76 (1)	0,76 (1)

* Mode 5 is failure in bolt shear.

Failure involving rotation of the bolt and subsequent pull-through or punching through the plate have been recognised in tests without washers for about 25 years and are reported by Stark and Toma (1978) for screwed connections and by Gilchrist and Chong (1979), who recommended that design equations be modified to account for this effect in thin plates. This mode of failure involves rotation of the bolt and bending of the end region of the plate back towards the bolt, with associated tears in the plate on both sides of the hole in front of the direction of loading.

Kim and Yura (1999) tested single- and two-bolt specimens in which the end distance and ratio of ultimate to yield stress of the plate material were varied. They confirmed that bearing stress is proportional to the ultimate stress of the material. In these tests the bolts were prevented from rotating and the pull-through mode of failure was avoided.

EVALUATION OF TEST RESULTS

Load-extension relationships

A typical load-extension curve is illustrated in figure 3 for specimen K13. The most important characteristics are as follows:

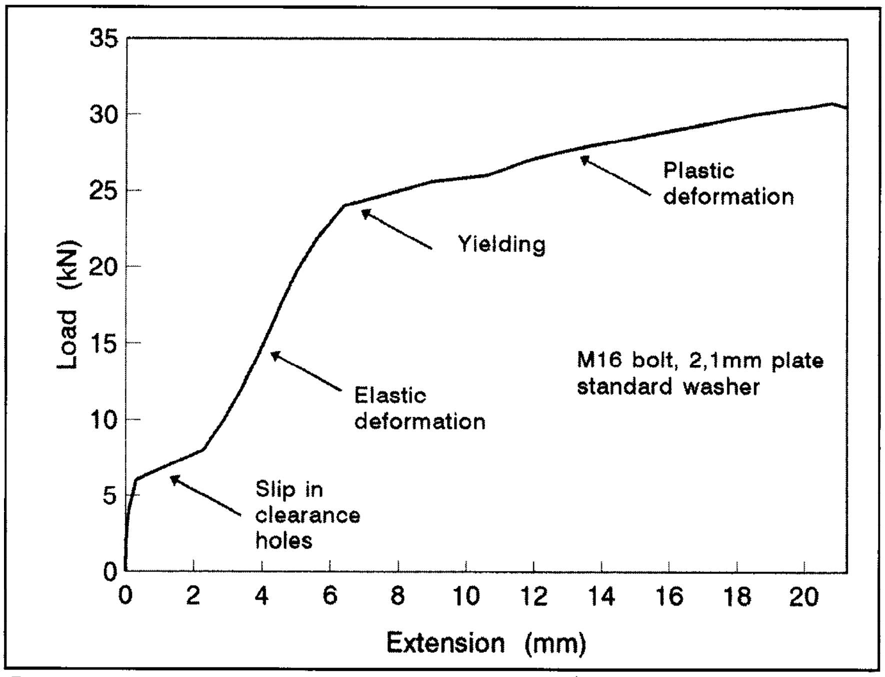


Figure 3 Typical load-extension relationship (test K13)

- As the bolt is hand-tightened with a spanner of normal size and located in a random position relative to the clearances in the bolt hole in the two plates, there is an early slip of the plates of between 0 and 4 mm to take up the clearance in the holes. This greatly increases the flexibility of the connection.
- A region of elastic deformation occurs before inelastic extension commences associated with one of the potential modes of failure described in the previous section.
- Large ductile extensions of the bolted connection occur before the maximum load is reached. Extensions at failure exceeded 9 mm in all specimens except those with no washers (NW) or those in which bolt failure occurred.

While the observed extensions of the specimens at failure, given in table 2, are important in ensuring that multiple bolt connections can be categorised as plastic for the purposes of moment redistribution and plastic analysis, attention should be given to the clearance in the bolt holes to avoid excessive elastic deformation.

Modes of failure and failure loads

Following the recommendations of Rogers and Hancock (1998b), the results of the 40 tests are analysed on the basis of the observed modes of failure. Comparisons are made in table 2 with the predicted failure load in the observed mode of failure, as well as the minimum failure load and associated mode of failure predicted by the code for the specimen from equations 1 to 3.

The four observed modes of failure considered earlier are described in the first column of table 3 and the number of occurrences of each mode is recorded and compared with the predicted mode of failure from equations 1 to 3 in the Canadian code. Apart from these modes of failure, two specimens failed due to bolt shear. A comparison is given in table 4 of the ratio of test load to predicted load in the actual mode of failure and the number of tests in which the predicted failure load is less than or greater than the test load. The implications of these results are discussed in the following sections of this paper.

Pull-through bearing failure

Pull-through bearing failure (mode 2) is clearly the most common mode of failure in the Kemp series, occurring in 17 of the 28 specimens. As indicated above, confusion exists over this mode of failure in the Canadian and South African cold-formed codes and the test results are therefore compared in tables 2 and 4 with the predictions in this code for conventional bearing failure involving hole elongation given in equation 1.

Table 3 Analysis of predicted and test modes of failure

			Predicted mode of minimum failure load in code: no of test		
Test mode of failure	Series	No of tests in this mode	1 Bearing elongation	3 End failure	4 Tension on net section
1 Bearing elongation	Kemp Rogers	2 12	 8	 4	2
2 Bearing pull-through	Kemp	17	4	2	11
3 End failure	Kemp Rogers	0 0			
4 Tension on net section	Kemp Rogers	7 0		1	6

Table 4 Analysis of failure loads in observed modes of failure

			Predicted failure load in actual mode		
Test mode of failure	Series	No of tests in this mode	Normalised failure load	Predicted number less than test load	Predicted number greater than test load
1 Bearing elongation	Kemp Rogers	2 12	0,74 0,70	0 0	2 12
2 Bearing pull-through*	Kemp	17	0,68	1	16
3 End failure	Kemp Rogers	0 0			
4 Tension on net section	Kemp Rogers	7 0	1,13	7	0

* Predicted load based on bearing failure due to elongation of the hole.

It is apparent from these predictions that this mode of failure occurs in the tests at lower loads than those predicted for conventional bearing failure. Furthermore, the results in table 3 indicate that for most of these specimens an alternative mode of failure is predicted by the code at loads greater than those observed in the tests.

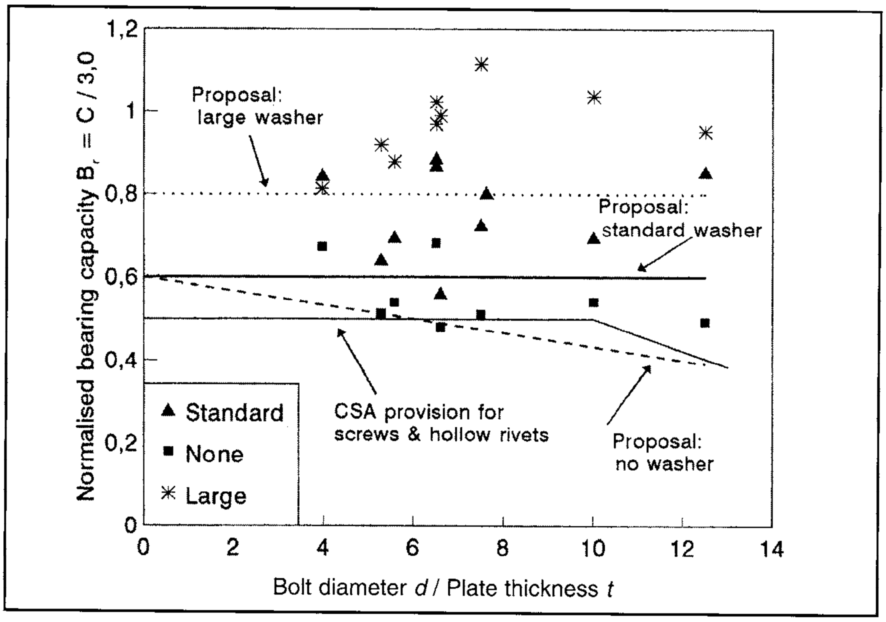


Figure 4 Test failure load as a function of ratio of bolt diameter to plate thickness: Kemp series

Normalised failure loads are obtained by dividing the observed ultimate load by the bearing resistance given by equation 1 with $C = 3$. These normalised failure loads in the mode of failure observed in the tests, as well as in the mode representing the minimum failure load in the code, are given in table 2. Apart from tests in which large washers are used, these ratios are significantly below 1,0 and at a level which indicates that the code considerably underestimates the bearing capacity in lap joints in which the bolts can pull-through the bolt holes. In a separate series of tests on bolted cold-formed channels back-to-back it is apparent in figure 1b that this mode of failure also occurs in these four-bolt connections due to the wide spacing of the bolts. Even though this mode of failure is less likely to occur in multiple-bolt lap joints or with thick plates, in a separate series of tests conducted by the author there was no increase in the bearing failure load per bolt in lap joints with two bolts in plates up to 2 mm thick.

These pull-through failures all occurred in specimens with either standard-size washers or no washers below the nut and the bolt. In a parallel series with large washers only one of the nine specimens failed in a pull-through mode. The increase in failure load of the connection from no washers to a standard-size washer and from a standard-size washer to a large washer is illustrated for the Kemp series in figure 4, in which the ratio of failure load to predicted load in the observed mode of failure is plotted as a function of the ratio of bolt diameter to plate thickness. An increase of approximately 20% in failure load is obtained by introducing normal washers and a further approximately 20% increase is achieved with the large washers. Apart from the specimens with no washers there is no apparent reduction in normalised strength in the pull-through mode of failure in figure 4 as the ratio of bolt diameter to plate thickness is increased. In fact, for large washers there is a slight trend for the strength to increase with this ratio. For a particular type of washer, or no washer, the ratio of bolt diameter to plate thickness does not significantly influence the mode of failure within the range of this ratio in the tests.

It is also apparent from table 2 that the normalised bearing capacity is not influenced by plate thickness in the range 1,6 to 3,0 mm. If the pull-through mode arises from plate bending due to eccentric moments in lap joints, this is not surprising because, for a constant width of plate, both the normalised bending resistance and the applied eccentric moment are proportional to plate thickness.

In the Rogers series, bearing failure occurred in all the specimens selected for comparison. No distinction is drawn by these authors between conventional bearing failure associated with elongation of the hole in the plate (mode 1) and pull-through failure of the bolt (mode 2). Despite the much higher plate strengths in most specimens in this series and the use of integral washers of standard size, it is apparent in figure 5 that the ratio of failure load to predicted load in the observed mode of failure is consistent with the measurements in the Kemp series on the specimens with standard washers. Rogers and Hancock (1998b) note that, considering all their tests, no significant variation exists in the bearing failure load as a result of the use of integral washers, although in the 12 tests extracted for comparison with the Kemp series it does appear that integral washers produce slightly higher failure loads in figure 5 than the standard washers. Contrary to Rogers and Hancock (1998a and b) there does not appear to be a consistent reduction in failure load of specimens with standard and integral washers with increasing values of the ratio of bolt diameter to plate thickness. The pull-through mode of failure may explain this inconsistency, which is also apparent in figure 4 for standard and large washers, although a reduction does occur in specimens with no washers.

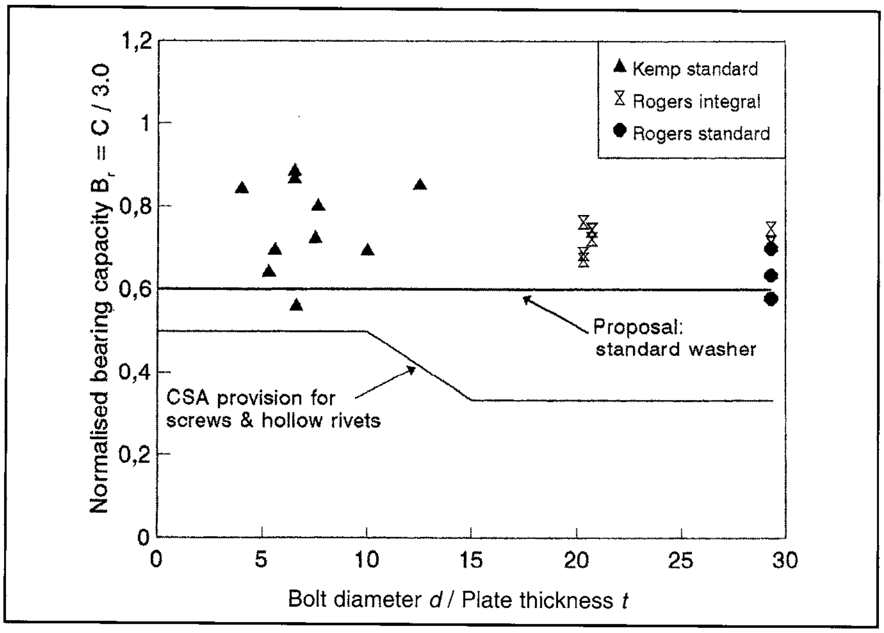


Figure 5 Test failure load as a function of ratio of bolt diameter to plate thickness: Rogers series and Kemp series with standard washers (SW)

If the provision in clause 7.3.5.3 in the code for screws or hollow rivets in lap joints is considered, an effective value of $C = 1,5$ applies up to $d/t = 10$ and is then reduced linearly to 1,0 for d/t above 15. This prediction is shown by the light solid line in figures 3 and 4 and represents a lower bound on all the results. It does not, however, account for the important influence of using standard or large or no washers as observed in the tests.

Tension failure

In seven tests (six with large washers and one with a normal washer) tension failure occurred in one of the plates across the net section reduced by the bolt hole (mode 4). This was the second most common mode of failure after bearing. In five of these seven tests this mode of failure is predicted by the Canadian code and the average ratio of failure load to predicted load in this mode is 1,13, reflecting an accurate and conservative prediction of the tests for design purposes.

Other modes of failure

End failures (mode 3) were avoided in all tests by selecting an end distance from the centre of the hole to the end of the plate of at least 2,4 bolt diameters. It should be noted, however, that as bearing failure developed at low loads in many specimens, these test results do not provide guidance on this mode of failure.

In two specimens with a 12 mm diameter Grade 4.6 bolt, failure occurred in bolt shear (mode 5). The predictions for bolt shear failure in the code are unduly conservative and are not considered further to avoid distorting the comparisons of actual and predicted bearing behaviour.

Design recommendations

In cases of isolated bolts used in bearing in lap joints on thin plates it is recommended, on the basis of the results in figures 4 and 5 and tables 2 to 4, that a pull-through mode of bearing failure should be recognised in design codes by limiting the bearing resistance to

$$B_r = Ctdf_u \qquad (4)$$

in which $C = 1,8$ for a standard washer under the nut and bolt head, $C = 2,4$ for a large washer under the nut and bolt head and $C = 1,8 - 0,05\ d/t$ for no washers. These reductions would apply to values of the ratio of bolt diameter to plate thickness in excess of 4, as represented by the tests.

In figures 4 and 5 these empirical relationships are normalised by dividing the values of C by $C = 3,0$ from the Canadian code. It is apparent that these three simple expressions provide a conservative assessment of most of the test results. A washer under the nut and head of the bolt should, however, be required for single-bolt lap joints, particularly for ratios of bolt diameter to plate thickness exceeding 4 where the hole clearance is greater than 10% of the bolt diameter.

Even though clearances in the holes are averaged out in multiple-bolt connections, it is desirable to limit the initial slippage by reducing the clearance in the holes to a minimum (eg 1 mm or 1,5 mm) depending on fabrication and erection procedures for bolts up to 16 mm diameter.

Under these conditions lap joints with bolts in bearing provide sufficient ductility without loss of bearing resistance to enable the joints to be designed as plastic hinges or as a source of moment redistribution.

CONCLUSIONS

If normal design procedures are followed, rotation and pull-through of the bolt is observed to be the most critical mode of failure in lap joints with single bolts in bearing on relatively thin plates (ratio of bolt diameter to plate thickness exceeding 4,0). The normal code provisions for bearing failure consistently overestimate the resistance in this mode of bearing failure.

Revised design criteria are proposed for determining this failure load, which provide an appropriate lower bound to the test results for the conditions of no washer, standard washer and large washer under the nut and bolt head. It is recommended, however, that at least a standard washer be provided under the nut and head of the bolt, particularly for ratios of bolt diameter to plate thickness exceeding 4,0 where the hole clearance exceeds 10% of the bolt diameter. To reduce slippage in the connection at low loads, the clearance should be reduced to a minimum (eg 1 mm or 1,5 mm) for bolts up to 16 mm diameter depending on fabrication and erection procedures.

If the above conditions are satisfied lap joints should achieve both the expected strength and sufficient ductility to design the joints as plastic hinges or as a source of moment redistribution.

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