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BOLTED TIMBER JOINTS

N.Harding and A.H.R.Fowkes

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Errata

Page 878, four lines from bottom of page, delete 8D and substitute 300 mm.

Page 880, Table 3, column headed PROP. LIMIT, row Significant Interactions, delete the righthand CE. Insert CE in row Significant Interactions in column headed ULTIMATE LOAD.

BOLTED TIMBER JOINTS

BY

N. Harding ONC(Const), HNC (Civil Eng)*
A.H.R. Fowkes CEng, MIStructE, MIPENZ*

ABSTRACT

This paper describes a series of tests carried out on bolted timber joints, loaded in shear, to investigate the effects of departures in end and edge distances, bolt hole and washer size, from the requirements of NZS 3603: 1981, Code of practice for Timber Design and to determine if any of these departures have a significant effect on joint performance which requires further investigation. The series is the first stage in a Building Research Association of New Zealand (BRANZ) research project intended to prepare design information on these joints in areas not presently covered by available codes of practice and timber design handbooks, and will be the subject of a BRANZ research report to be published.

1. INTRODUCTION

A survey of past research literature [1] confirmed a previously held suspicion that insufficient detailed and replicated information existed on bolted timber joints loaded in shear. The relevant provisions of NZS 3603 [2], are thus based on sparse data and the selection of some of the limiting criteria in the code must perforce, be arbitrary. Some data indicated that present code provisions may be unduly restrictive.

From a field study of the construction of bolted timber joints and the components used in them by the New Zealand building industry two aspects emerged. First, there was a wide lack of confidence in the present design requirements for joints loaded in shear. They were considered to be based on component tests of only limited relevance to the behaviour of a structure as a whole and to make no allowances for conditions occurring in practice. Second, and probably as a consequence, the code provisions for such joints were commonly violated and seldom enforced.

This tacit adoption by the industry of apparently lower safety factors reinforced the need felt for a research programme to determine basic design information for bolted timber joints having a range of end and edge distances, washer, and bolt hole sizes.

The tests reported in this paper were carried out to investigate the effects on the performance of bolted timber joints loaded in shear, of a limited number of variations in specification including the departures from the code most often seen in the industry survey.

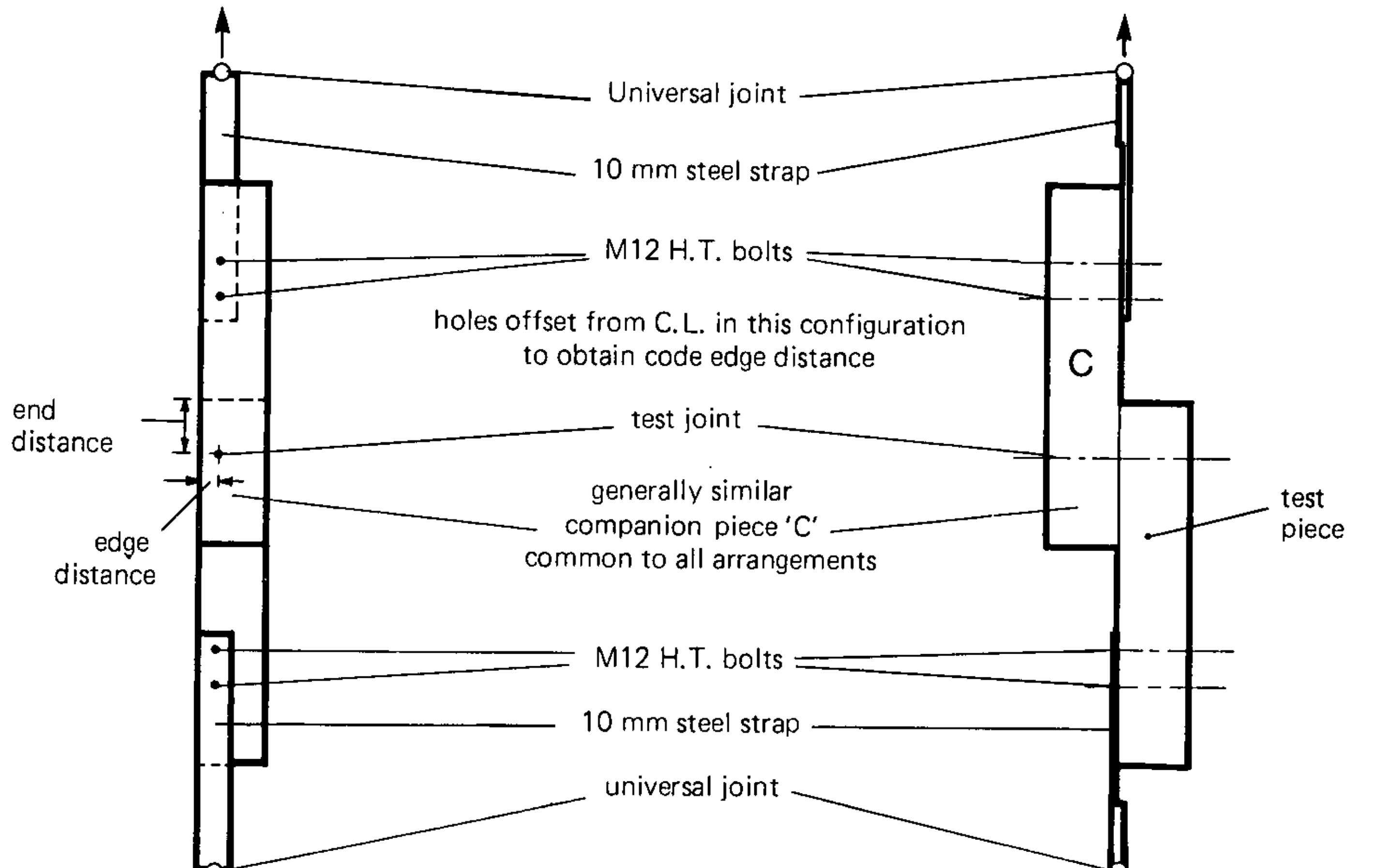
2. EXPERIMENTAL DESIGN

The programme was designed to compare the performance of code joints as controls with that of joints which deviate from the code in details of end and edge distances, bolt hole diameter, and washer size by determining, proportional limit, yield point, and ultimate load derived by computer analysis of continuously recorded load/displacement data for the joints tested.

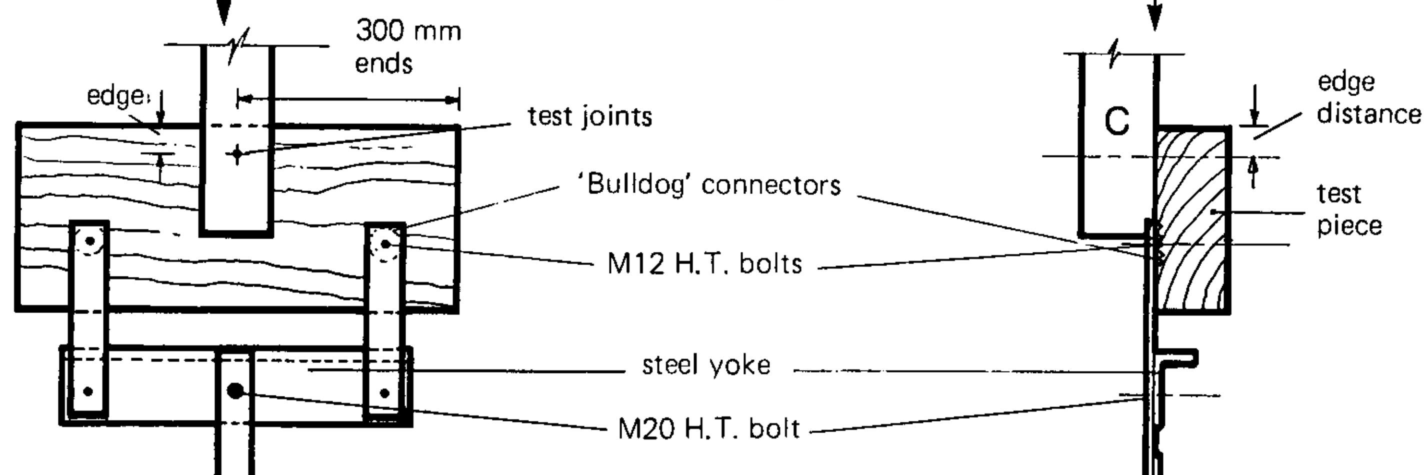
To investigate the selected parameters the compression test arrangement used by other researchers in the past and currently specified in timber testing standards [3] was considered inappropriate since reducing end distance is likely to have little effect on joint performance when compressive loads are applied. It was therefore resolved that test joints should be pulled at a constant straining rate.

* Structures Division, Building Research Association of New Zealand (BRANZ)

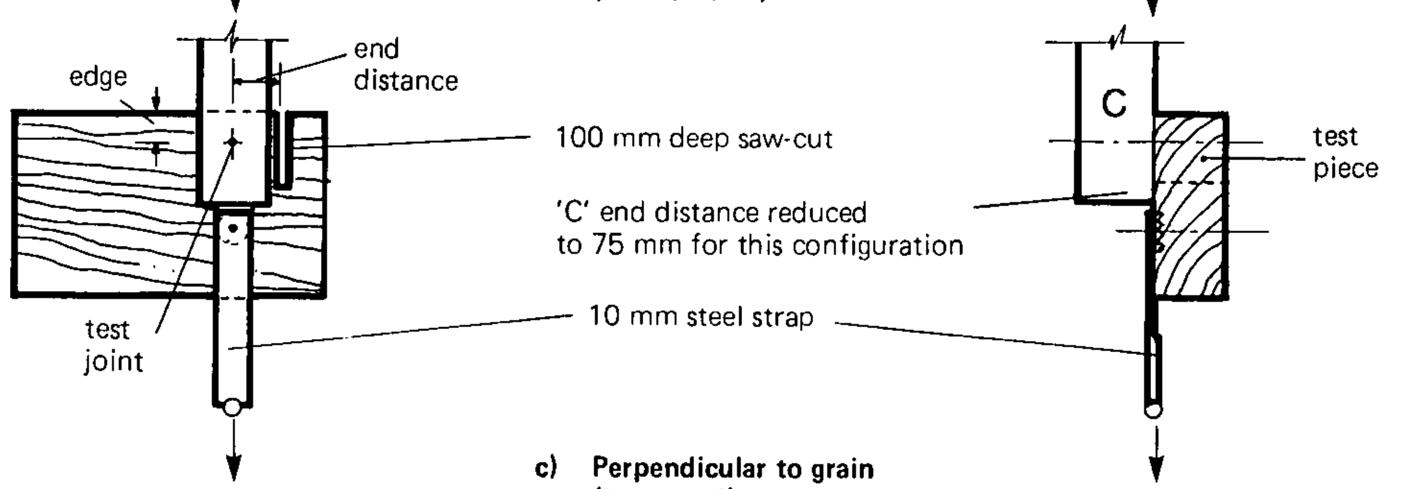
General Test Arrangements



a) **Parallel to grain**



b) **Perpendicular to grain (centre-beam)**



c) **Perpendicular to grain (beam-end)**

Figure 1

All specimens were two-member, single-bolt joints [Fig. 1] with the line of action of the tensile force passing through the shear plane of the joint. Basic working loads for such joints given in NZS 3603 are derived from standard loading tests such as those given in AS 1649-1974 [3], which specify the application of a compressive load to three-member joints acting in double shear. Reasons for this are obscure except that testing is easier. The use of two-member joints was selected on the following grounds:

- A large number of bolted joints seen in practice act in single shear.

- The greater bolt rotation in two member joints of low slenderness ratio (small timber thickness) cannot be accurately assessed using three member joints.

- Indications from earlier research [4] are that although the ultimate strength of double shear joints is equivalent to that of single shear joints (of twice the thinner member thickness) the behaviour at other load levels is somewhat different, e.g.:

  a) The proportional limit load is much higher for three member joints than two member joints.

  b) Reductions in washer size influence the performance of three member joints much less than that of two member joints.

As control joints were expected to differ in behaviour according to whether they were constructed with the load applied parallel to, or perpendicular to the grain, and according to whether they were assembled and tested while green (i.e., moisture content greater than 30%), or assembled green and tested dry (mc less than 18%) after conditioning, test joints were constructed in four series to allow for these differences which are provided for in the code:

- parallel to grain
  constructed wet, tested wet

- parallel to grain
  constructed wet, tested dry

- perpendicular to grain
  constructed wet, tested wet

- perpendicular to grain
  constructed wet, tested dry.

As density has traditionally been considered a useful guide to strength, each test series was duplicated using high and low density Pinus radiata, the most commonly used building timber in New Zealand.

In each of the resulting eight sub-series, 16 test samples were constructed to include code joints and joints incorporating specific departures from the code, i.e.: reduced end distances, reduced edge distances (perpendicular to the grain samples only), oversize bolt holes, and smaller washers, and timber thickness treated as a variant although it is provided for in the code.

The factorial method of design used all 16 possible combinations of code value and variation in the sub-series tested parallel to the grain, and a balanced half of the 32 possible combinations in the sub-series tested perpendicular to the grain.

Only the test piece in each two member specimen incorporated variations in bolt hole size end and edge distances, but the other variables were incorporated in both members.

Only the two levels of each variable shown in the following table were considered to enable a first estimate of the relationships of the effects and interactions to be derived as a guide to variants requiring further investigation and the direction this should take.

TABLE 1 : SPECIFICATION FOR CONTROL JOINTS AND VARIATE JOINTS

Basis for selections shown in brackets.

	CONTROL JOINT	VARIATE JOINT
Timber nominal size	100 mm thick (effective maximum)	50 mm thick (common minimum)
Perpendicular to grain		
Edge distance	48 mm (4D) (code minimum)	24 mm (2D) (practical minimum)
End distance	300 mm (Judged remote from end effect)	48 mm (4D) (British code minimum [5] No NZ code requirement.)
Parallel to grain		
Edge distance	24 mm (2D) (code minimum)	No variation (no variations seen)
End distance	96 mm (8D) (code minimum)	36 mm (3D) *60 mm (5D) (commonly seen)
Bolt hole diameter (D)	13.5 mm (D+1.5 mm) (code maximum)	15.9 mm (commonly used)
Washer size	50 x 50 x 3 mm thick (code minimum)	32 mm diameter x 3 mm thick (very commonly used)

* Intermediate value incorporated into additional sub-series of 16 specimens only, tested wet.

A 12 mm diameter hot dip galvanised engineers bolt and nut was used in each joint. All washers hot dip galvanised.

3. TEST PROCEDURE

Test joints were subjected to low-speed, monotonic loading as specified in AS 1649-1974 which is in general accord with past research practice. The test arrangements differed from those for standard bolt tests in that joints were loaded in tension - necessary to evaluate the effects of reductions in end and edge distances. Load/displacement data were recorded continuously up to true ultimate load and the failure type noted. Density and moisture content of each specimen were determined immmediately after test.

4. ANALYSIS OF DATA

The characteristic load/displacement curve of a laterally loaded bolted joint may be considered in four stages: a short, low-stiffness, first stage, during which bolt slack is being taken up; a relatively constant stiffness second stage up to the limit of proportionality; a 'knee' stage of reducing stiffness; and a final, fourth stage of low-stiffness yield deformation.

The third stage could more properly be considered a merging of stages two and four with the nominal point of change being the 'yield point' of the joint. Actual assessment of this point is somewhat subjective and so the Forest Research Institute (FRI) definition of yield point as the intersection of the load/displacement curve with a straight line parallel to the approximately linear part of the loading curve but offset by 5% of the bolt diameter along the displacement axis was adopted. The initial slope is taken as the line joining the two points at which the slope of the loading curve is 70% of the maximum.

For the purposes of this investigation the higher of these two points was taken as a consistent assessment of the limit of proportionality. Similarly the intercept of the initial slope on the displacement axis has been assumed as the initial take-up distance. Between yield and ultimate load points two other arbitrary points at displacements of take-up distance plus, respectively, one half and one bolt diameter (0.5 D and 1.0 D points) were included to provide intermediate data also related to bolt size. The points considered during analysis are shown in Figure 2. Statistical analysis of the data pertaining to each of the points on the load/displacement curve then allowed an assessment of which factors caused significant effects at each load level.

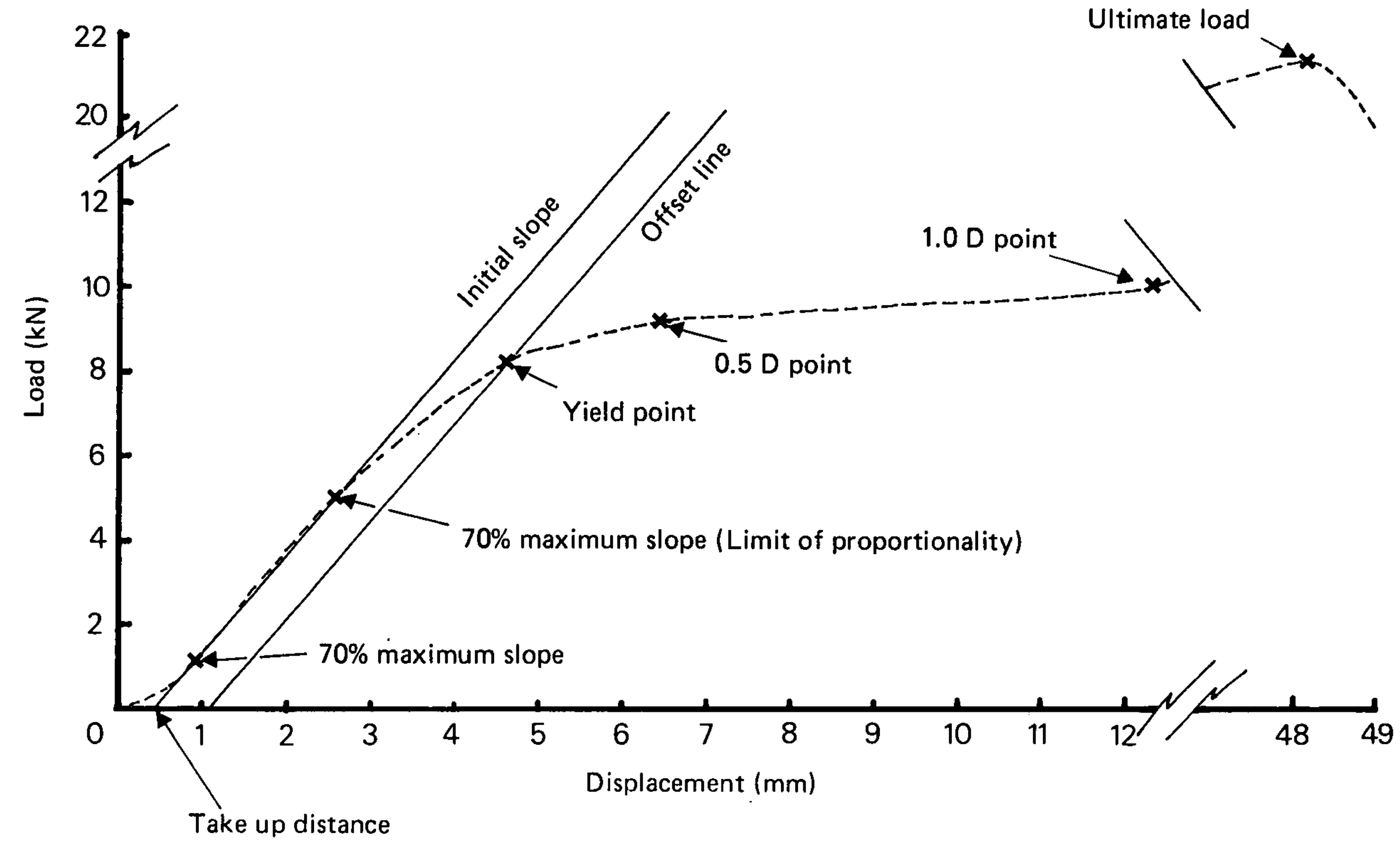


Figure 2

5. RESULTS

Tables 2 and 3 summarise the test results for load measurements. These tables show the main effects, which are the differences between 2 sets of joints which are similar for all factors except the one being evaluated. Thus the main effect for factor A (say), is the average difference between a group of joints with 8D end distance and various combinations of washer size, bolt hole diameter, etc, and a group of joints with 3D end distance and the same set of combinations of washers, bolt holes etc.

These differences do not represent deviations from the 'control joints' which have code values for all factors. Test values for the control joints are shown at the top of the tables, as indications of the load levels at which the effects of the factors were evaluated.

Joints Loaded Perpendicular to the Grain

The main effects on load are shown in Table 2, which also notes that there were some significant interactions, but these are not detailed.

TABLE 2: LOADS PERPENDICULAR TO GRAIN EFFECTS OF VARIATIONS

FACTOR VARIATE		PROP. LIMIT DRY	WET	YIELD POINT DRY	WET	ULTIMATE LOAD DRY	WET
CONTROL		2.64 kN	3.00 kN	5.57 kN	5.78 kN	11.11 kN	12.09 kN
End Distance	(A)	N/S	N/S	-3.4**	N/S	-3.1**	-1.6**
Edge Distance	(B)	N/S	N/S	-2.3**	-2.5**	-4.3**	-3.7**
Slenderness	(C)	+1.4**	N/S	N/S	N/S	N/S	N/S
Hole Size	(D)	N/S	N/S	N/S	N/S	N/S	N/S
Washer Size	(E)	-1.0**	N/S	N/S	N/S	N/S	-1.1**
Significant Interactions				AE	AE BC BD	AB	AE BC

** Indicates statistical significance at the 99% confidence level
N/S Indicates no statistical significance at the 99% confidence level.

In most of these cases, where either of the factors was assessed in joints with the control value of the other factor, there was a greater reduction in strength than is shown in the table. But in joints incorporating one of the variations, use of the other variation as well did not give as great an extra reduction as the main effect shown in the table.

For example, the end and edge interaction for ultimate load, dry joints: the edge distance factor (B) reduces edge distance from 4D to 2D, and causes, on average, a decrease in strength of 4.3 kN, as shown in the Table 2. However, when this change in edge distance is made on joints with an end distance of 300 mm (control value for end distance factor A) the decrease in strength is 6.3 kN. But the same change in edge distance (B) on joints with an end distance of 4D (A) is 2.3 kN.

The behaviour of joints loaded perpendicular to the grain was dominated by the effects of reductions in end and edge distances. The ultimate loads achieved by joints with reduced end or edge distances were of the order of 50-60% of those for control joints. The overwhelming effects of reductions in either of these two factors on ultimate load masked the effects of the other variations on ultimate joint performance.

Of note was the failure pattern of low-slenderness joints incorporating control values for end and edge distances. In 75% of joints tested this took the form of a tension rupture perpendicular to the grain of the timber some distance below the line of the bolt hole and thus an actual failure of the connection as such did not occur. Ultimate load and displacement values were comparable with those of the remainder of these joints, failure of which differed only in that the tension rupture occurred on a line passing through the bolt hole.

The reason for this appears to be the method of test which differs from previous methods in that tension and some degree of bending is applied perpendicular to the grain of the timber as joint deformation occurs. Given the known incidence of similar timber stress in practice, this factor should perhaps be included as a design consideration for bolted timber connections.

The failure pattern of similar high-slenderness joints differed considerably, splitting first occurring along the grain on the inner surface of the joint in the region of the bolt hole, gradually extending along and across the grain until separation. With reduced edge distance a similar failure pattern was observed but the initial split occurred at considerably lower loads and displacements and a rapid extension to ultimate separation followed. For all joints incorporating the reduced end distance value, failure took the form of a sudden separation along the grain between the bolt hole and the end; this split extended rapidly along the remaining length of the member.

With ultimate load displacement for joints with reduced end or edge distances being generally less than 6 mm, the displacement beyond the proportional limit was small. In fact 25% of these joints did not reach the yield load as defined by the FRI algorithm. No analysis of loads at 0.5D and 1.0D displacement was possible because too few values of load were available at these points.

The joints tested wet ranged in moisture content from 27.4-119.4% with a mean of 62%. The effect of increasing moisture content was to slightly reduce the yield point loads and to significantly (at the 5% level) reduce ultimate loads. At the proportional limit and yield loads, before the effects of reduced end and edge distances became predominant, the effects of other factors were as follows:

Slenderness:	Reduction of this factor from 8 to 4 (100-50 mm timber) resulted in slightly lower proportional limit loads for wet joints. Dry joints showed, surprisingly, an increase in proportional limit load for this reduced timber thickness.
Washer size:	Lower proportional limit loads were attained by dry joints incorporating smaller, 32 mm diameter washers this effect being more pronounced in low density timber.
Bolt-hole size:	An increase of 2.4 mm in hole size resulted in an increase in the yield load in joints with an end distance of 8D. This unexpected effect was merely suggested by the wet joint results but was significant at the 1% level for dry joints.
Timber density:	Joint performance was not affected by this factor.

Joints Loaded Parallel to the Grain

For joints loaded parallel to the grain, reduction of end distance from the code value of 8 x bolt diameter (D) was the dominant factor reducing the level and displacement of the ultimate load point. At an end distance of 3D loads at a displacement of 1D were also significantly reduced. Reduction of end distance had no affect on strength at lower displacements.

Reductions in ultimate load values for joints incorporating an end distance of 3D were of the order 50-55% of those for control joints. For the wet joints with an end distance of 5D this reduction was much less, of the order of 20-25% of the control value.

Ultimate load displacement was similar for both wet and dry joints incorporating the 8D end distance. This was also apparent with 3D joints although at roughly half the value. The intermediate 5D end distance (which was only used for wet joints) gave an intermediate ultimate load displacement value.

For joints with end distances of both 8D and 5D the pattern of failure generally took the form of a tensile split running from bolt hole to end. A notable exception occurred for 75% of the wet joints incorporating an 8D end distance and a washer size of 32 mm diameter which failed due to timber crushing under the washer.

For joints incorporating an end distance of 3D, failure in all cases was by means of the bolt forcing a plug of timber out of the end grain face.

Significant effects on joint behaviour from other factors were also apparent. These effects differed considerably between the wet and dry joints and may be summarised as follows:

Slenderness & Washer Size:	For wet joints a reduction in timber thickness combined with a reduction in washer size from 50 x 50 mm to 32 mm diameter consistently reduced loads and increased displacements. When only one of these variations was used the decrease in strength was less, and reached significance level only beyond the yield point. These effects were not observed in the dry joints. Use of the small washer appeared to lessen the effect of the reduced end distance in dry joints.
Bolt-hole size:	Increasing bolt-hole size by 2.4 mm caused no significant effect on joint performance.
Timber density:	Wet joints were unaffected by variations in density but lower densities were found to cause a significant reduction in the yield point and ultimate loads in dry joints.
Moisture Content:	Variations in moisture content within the dry and the wet ranges did not significantly affect joint performance.

TABLE 3: LOADS PARALLEL TO GRAIN MAIN EFFECTS OF VARIATIONS

FACTOR VARIATE			PROP. LIMIT	YIELD POINT	0.5 D	1.0 D	ULTIMATE LOAD
				WET			
CONTROL			4.37 kN	7.27 kN	8.50 kN	10.99 kN	28.97 kN
End	(A)	3D	N/S	N/S	N/S	-1.1**	-12.3**
Distance	(A')	5D	N/S	N/S	N/S	N/S	-5.6**
Slenderness	(C)		N/S -1.5*	N/S -2.7**	-1.9** -2.6**	N/S -2.1**	-4.3** -4.9**
Hole Size	(D)		N/S	N/S	N/S	N/S	N/S
Washer Size	(E)		N/S -2.0**	N/S -3.1**	N/S -1.4**	-1.3** -3.0**	-3.4** -4.0**
Significant Interactions			CE CE	CE	CE	CE	
				DRY			
CONTROL			5.99 kN	8.02 kN	9.17 kN	11.12 kN	31.15 kN
End Distance	(A)		N/S	N/S	-1.8 a	-5.9**	-17.0** -10.1**
Slenderness	(C)		N/S	N/S	N/S	N/S	N/S
Hole Size	(D)		N/S	N/S	N/S	N/S	N/S
Washer Size	(E)		N/S	N/S	N/S	N/S	-8.1** N/S
Significant Interaction							AE

** Indicates statistical significance at the 99% confidence level
* Indicates statistical significance at the 95% confidence level
a Indicates statistical significance at almost the 95% confidence level
N/S Indicates no statistical significance at the 95% confidence level.

Values for interacting factors are shown split the top value being for joints with control values of the interacting factor and the lower with variate values of the interacting factor.

6. DISCUSSION

The test programme was designed to identify which variations from the code specification had a significant effect on joint performance, not to establish absolute values for joints with such variations.

However it is possible to compare the performance of the limited numbers of code joints tested with NZS 3603 [2] values for Radiata pine 100 mm thick, 12 mm bolt, under brief loading:

Perpendicular to the grain

Code values:	Dry : 3.54 kN,	Wet : 2.48 kN
Test values:	Dry : 3.33 kN,	Wet : 2.55 kN

Parallel to the grain

Code values:	Dry : 4.64 kN,	Wet : 3.24 kN
Test values:	Dry : 7.94 kN,	Wet : 6.26 kN

The test values are based on density adjusted mean ultimate loads divided by 4 as specified in NZS 3603 and AS 1649. It is not known on precisely what basis the code values were derived since the 5% lower probability limit of ultimate load divided by 2.8 is an alternative criterion.

The test values for perpendicular to the grain are remarkably close to the code values, but those for parallel to the grain are much higher. The reason for this appears to be that an alternative criterion of load at some (unknown) arbitrary displacement has been used.

Loading perpendicular to the grain

Ultimate failure was always by splitting i.e. tension perpendicular to the grain. For joints with a reduced edge distance failures were commonly brittle and at low loads and displacements. The direct tension applied in the single shear test arrangement , coupled with a certain amount of cross-grain bending, in most cases initiated splitting on the bending tension side of the joint. Since many joints will in practice be loaded in such a manner this behaviour is regarded as typical and indeed failures of this type have been seen in the field (e.g. purlins loaded by wind uplift).

Currently the code loads are based on limiting values of either the compressive stress perpendicular to the grain or bolt yield. Observations during these tests indicated that this is likely to reflect joint behaviour only at small displacements.

No minimum end distance is specified in NZS 3603 for joints loaded perpendicular to the grain but a significant difference was found between the strength of the short and long end distance joints tested. This situation is in need of rectification and almost certainly further testing is needed to establish limiting end distances for the code design loads.

As the effects of end and edge distance were so dominant at ultimate load level further testing is also required to establish any possible effects of hole size and washer size on the ultimate load performance of these joints.

Increasing timber density is traditionally related to increasing strength. For joints tested perpendicular to the grain this relationship was not found. The reason appeared to be that failures were a function of tension perpendicular to the grain for which density does not correlate with strength [6].

Loadings parallel to the grain

In green timber joints, even with considerable reductions in end distance, safe loads derived from test ultimate loads exceeded the code allowable loads indicating that present code loads provide a large safety factor for static loading. In dry timber joints however, the reductions are more severe. Further testing of joints incorporating intermediate values for end distance will be required to completely assess the effects of variations in this factor.

Factors which affect the proportional limit and yield point levels, and initial stiffness of joints are of greater significance to serviceability since they affect performance in the working range. Performance at these load levels with regard to code allowable loadings was adequate for all dry joints and for wet code joints tested and for similar joints incorporating the enlarged bolt hole size and reduced end distances. However, the use of smaller washers, notably in joints of lower slenderness ratio, reduced performance of wet joints in some cases to a critical level. Slenderness was highly significant in its effect on stiffness of dry joints, reduction of initial slope gradients were in the order of 40% when slenderness ratio was decreased, and take-up distance for these joints increased significantly. Both factors should be studied in detail in future test series.

Bolt hole size

The lack of any adverse effect from the increase in bolt hole size was somewhat surprising. Some effect was expected with regard to take-up distance and, especially in interaction with the smaller washers, on deflections at higher load levels. The effects resulting from this size increase of 2.4 mm instead appeared if anything to be beneficial to joint performance.

The use of a larger bolt hole size than currently allowed by NZS 3603 (bolt diameter + 1.5 mm) would be desirable in principle to decrease problems associated with shrinkage splits and driving which occur in practice and this factor will therefore be retained in future test series to hopefully confirm its lack of significant effect under a wider range of conditions and to include further enlargement of hole size.

7. CONCLUSIONS

Results of initial testing of bolted timber joints loaded in shear indicate that some of the provisions of NZS 3603 require re-examination.

In particular further testing of joints loaded perpendicular to the grain is required. At present end distances are not controlled by the Code. However, the results suggest that this factor has a marked effect on joint performance which should be more closely quantified and allowed for in the code.

The ultimate failure mode (of perpendicular to the grain joints) was shown to be an effect of tension applied perpendicular to the grain not normally modelled by current standard tests. The incidence of similar failures in practice suggests that more significance should be given to this effect in testing and design codes.

The finding that density was not related to the strength of joints loaded perpendicular to the grain indicates that it is inappropriate, for these joints at least, to use the NZS 3603 reference density modification.

Results for joints loaded parallel to the grain suggest that reductions in end distances of the order of those commonly seen in practice do not seriously reduce strength below that allowed for in the code for static loads.

Increased bolt hole size appeared if anything to be beneficial to joint performance. If this can be confirmed on further evaluation, it would be a desirable amendment to decrease practical problems associated with assembly and subsequent shrinkage.

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