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Development of All-Wood Connections with Plywood Flitch Plate and Oak Pegs

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Abstract: This paper proposes a new method for beam-beam connections, which include plywood as slot-in plates connected by oak pegs. A total of 96 specimens were fabricated for tests to explore the minimum required end distances and spacing between pegs parallel to the grain. A new failure mode, termed shear wedge that is different from those found in previous research, was found. A spring model was also proposed in this study to investigate the stiffness of the connections, and feasibility of EC5 to be applied on the new proposed connections was also examined. The effective number was discussed in this study and modified in accordance to the experimental results. The result of this study shows the new connections proposed do not lead to brittle failure unless failure in plywood occurred.

Key words: dowel-type connections, timber structures, timber connections, oak pegs.

1. INTRODUCTION

This paper deals with connections adopted in "heavy" timber framing. Heavy timber framing refers to the structural use of timber in large sections in which the members are relatively stiff compared to the connections. Such framing is most commonly used in braced post and beam structures and differs from the more common stick timber framing in which many small timber sections of low grade are joined together frequently and are most commonly braced by sheathing. The fastener in such a connection can be referred to as a dowel or peg.

A yield model was proposed by Johansen (1949) and developed by Larsen (1973) to predict capacity of symmetrical steel dowelled three member timber connections based on a range of potential failure modes. This model is usually called "European Yield Mode" (EYM). Extensive research has been carried out investigating the structural behaviour of connections not only with a single steel dowel (Santos *et al.* 2009; Sawata *et al.* 2006; Smith *et al.* 2005; Daudeville *et al.* 1999), but also with multiple pegs (Xu *et al.* 2009; Cointe and Rouger 2005; Quenneville and Mohammad 2000). One of the key issues in adapting the EYM in design is that the modelling approach is only appropriate to multiple fastener connections if they exhibit ductile failure (Murty *et al.* 2007). To avoid brittle failure, current practice in Europe tends to the use of many smaller diameter steel dowels instead of few large diameter ones. Another key issue of EYM is that the maximum load is linearly proportional to the number of pegs. However, the current design code, such as Eurocode 5 (EC5), Load and Resistance Factor Design (LRFD) and design rules proposed by Canadian Standards Association (CSA) adapt the effect number, n_{ef}, to give a conservative prediction

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of the load-carrying capacity of connections with multiple pegs. It appears that no agreement can be found between these design codes when considering the effective number of connections with multiple pegs (Jorissen 1998).

Steel slot-in plates have long been used as a central member, or flitch, of connections with steel dowels. Problems have been found with this type of connection for example; brittle failure of the connections is often observed in testing, the steel material is susceptible to corrosion due to environmental exposure and the exposed steel flitch plates and steel dowels will generally require intumescent treatment or encasing behind sufficient timber to allow charring protection against fire. Hence, non-metallic connections have attracted more and more attention. Non-metallic connections can be found in traditional tenon-mortice joints, which have been widely investigated. Shanks *et al.* (2008) tested 168 specimens of all-softwood connections to determine the minimum end distance and edge distance to prevent brittle failure. Sandberg *et al.* (2000) tested 72 specimens with red oak pegs driven through pine and maple base materials to investigate the influence of tenon fibre orientation and mortice thickness. They further proposed a model to predict the stiffness of the joints. MacKay (1997) tested typical US carpentry connections with a stiff oak peg in softwood connection material and proposed additional yield and failure modes to Johansen's yield modes. Whilst past research efforts were mainly put on tenon-mortice connections, this study aims at proposing a new beam-to-beam connections system that employs oak pegs and plywood slot-in plate.

2. EXPERIMENTAL PROCEDURE

2.1. Specimen Material

Throughout this study, spruce (*Picea abies*) glulam has been used to provide the side members of the test specimen, whilst 18 mm thick plywood was selected as the central member. American White Oak (*Quercus alba L.*) pegs of 16 mm diameter were used throughout the tests.

2.2. Material Tests

Material tests conducted in this study include bearing strength tests of the side and central members parallel to grain and bending and shear tests of the pegs. During the fabrication of the specimens material samples from the side member of each specimen were taken out for the bearing tests so that the bearing strength of each specimen could be determined. The samples taken for the bearing tests measured 80 × 80 × 40 mm. A 16 mm diameter hole was predrilled at the top before testing, as

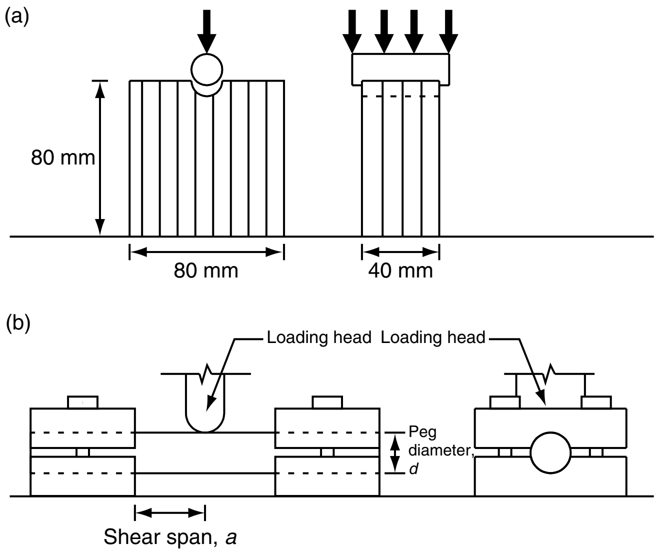

Figure 1. (a) Test apparatus for bearing strength test; (b) Test apparatus for fixed-fixed ends bending test

shown in Figure 1(a). The average bearing strength of the side members is 23.74 N/mm^2 with a standard deviation of 2.96 N/mm^2. A total of 30 plywood samples were tested each measuring 80 × 80 × 18 mm. The average bearing strength of central member is 60.15 N/mm^2 with a standard deviation of 5.30 N/mm^2.

A total of 30 pegs of 16 mm in diameter and 224 mm in length were selected for three point bending tests to determine the equivalent yield moment defined as the bending moment at which rapid loss of load resistance was observed. Yield moment is a parameter typically used in modeling the performance of dowel type connections. The average equivalent yield moment capacity of these pegs is 39.74 kN-mm with a standard deviation of 7.21 kN-mm. When a timber peg is subjected to bending, the strength of the peg is found to increase with the decrease of the shear span. This is due to the influence that shear has on peg failure at small shear spans. This study conducted fixed-fixed end bending tests on the pegs, the test apparatus is illustrated as Figure 1(b). The span ratio, which is defined by the ratio between shear span and peg diameter in Figure 1(b), ranged from 1 to 8.75 with six specimens for each span ratio.

2.3. Connection Tests

This study proposes a new method of beam-to-beam connection as shown in Figure 2 (a). To simulate the connections, a total of 96 connection specimens were tested as depicted in Figure 2(b). To determine the minimum end distance, a_{3t}, as shown in Figure 2(b), a series of connections with single peg were fabricated. The end distances include 1.5, 2.5, 3.5 and 4.5d,

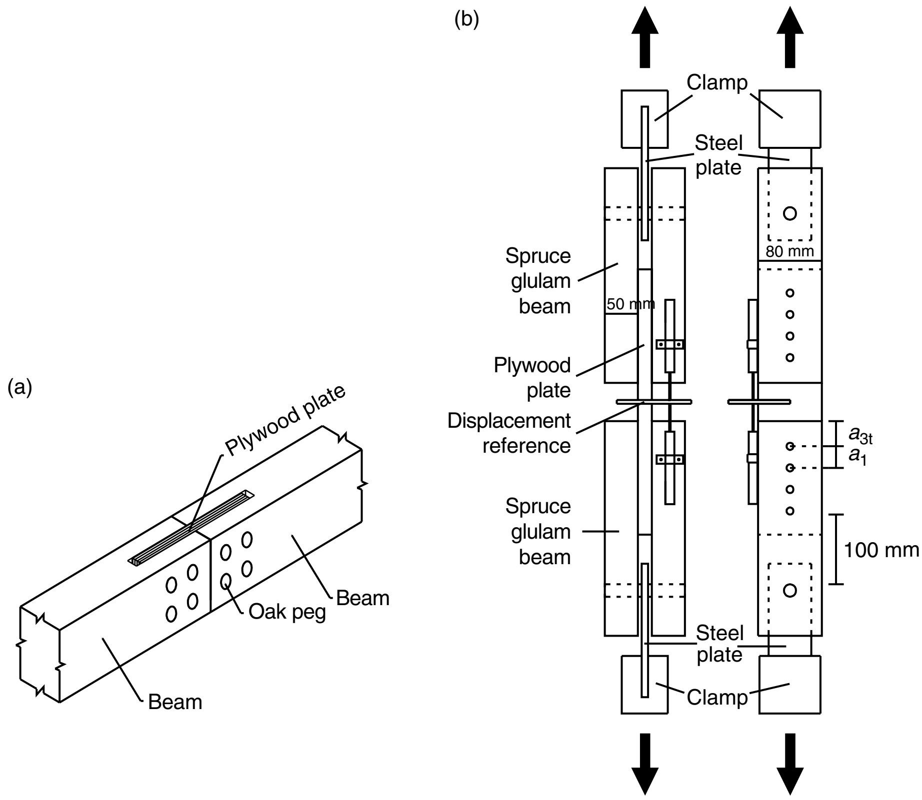

Figure 2. (a) The beam-to-beam connections; (b) The connection specimens tested

where d is the diameter of peg. Another two series of tests were carried out to investigate the minimum spacing between pegs parallel to the grain, a_1. The end distance of the first series of the two was fixed as 2.5d with varying spacing a_1 of 2, 3, 4 and 5d; whilst another series fixed the end distance as 3.5d with the same variations of spacing a_1 as used in the previous series. To discuss the effective number of fasteners parallel to the grain, termed n_{ef} in EC 5, two series of tests were planned. One of these two series has three and another has four pegs. Both series have 3.5d end distance with 3 and 4d spacing a_1. The experimental programme for connections tested is provided in Table 1.

Table 1. Experimental programme for connection tests

Series	Experiment	a_{3t} (d)	a_1(d)	No. of peg in row	Replicas
A	A-15-1~A-15-6	1.5	–	1	6
	A-25-1~A-25-6	2.5	–	1	6
	A-35-1~A-35-6	3.5	–	1	6
	A-45-1~A-45-6	4.5	–	1	6
B	B-20-1~B-20-6	2.5	2	2	6
	B-30-1~B-30-6	2.5	3	2	6
	B-40-1~B-40-6	2.5	4	2	6
	B-50-1~B-50-6	2.5	5	2	6
C	C-20-1~C-20-6	3.5	2	2	6
	C-30-1~C-30-6	3.5	3	2	6
	C-40-1~C-40-6	3.5	4	2	6
	C-50-1~C-50-6	3.5	5	2	6
D	D-20-1~C-20-6	3.5	3	3	6
	D-30-1~C-30-6	3.5	4	3	6
E	E-20-1~E-20-6	3.5	3	4	6
	E-30-1~E-30-6	3.5	4	4	6

A universal test machine was used to apply the monotonic tension load to the connections at load rate of 0.2 mm/min, loading the pegs in double shear. The load was terminated when the strength of the connection dropped to less than 40% of the ultimate strength. Figure 2(b) illustrates the experimental setup. Each specimen consists of two connections, to be tested simultaneously, on which two LVDTs are mounted to measure the displacements from a relatively static reference point. When one of the two connections failed in tension, the specimen can no longer withstand loading, and the data obtained from weaker connections will be used to analyse the performance of the specimen. Data from the other will be disregarded. To obtain the stiffness and strength of the connections, the data ranges from 20–40% of the peak load were used to take the regressive line. The slope of the regressive line aforementioned is regarded as the stiffness of the connections. The regressive line was then offset 5% of the peg diameter (0.8 mm). The load where load-displacement curve intersects the shifted regressive line is termed yield strength.

3. RESULTS

Five different failure modes were observed during the experiments, as shown in Figure 3. Failure Mode I, II and III were observed only in single peg connections (series A); failure mode III, IV and V occurred in multiple peg connections (series B, C, D and E).

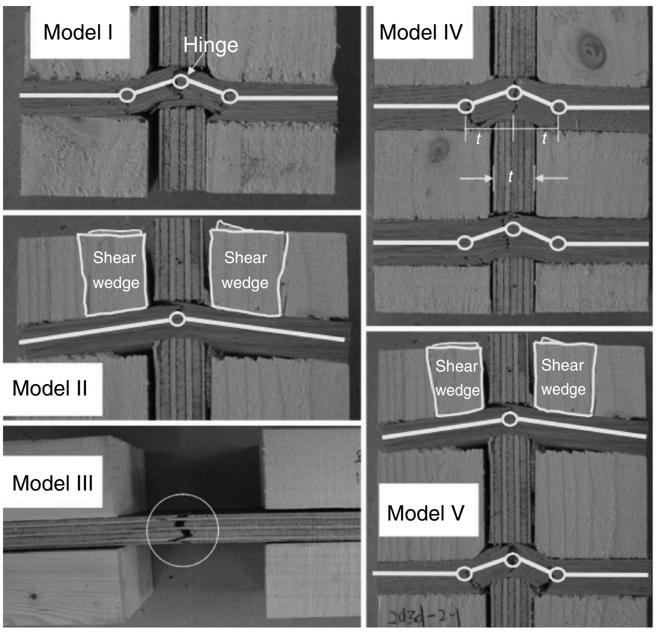

Figure 3. Failure modes observed from the tests

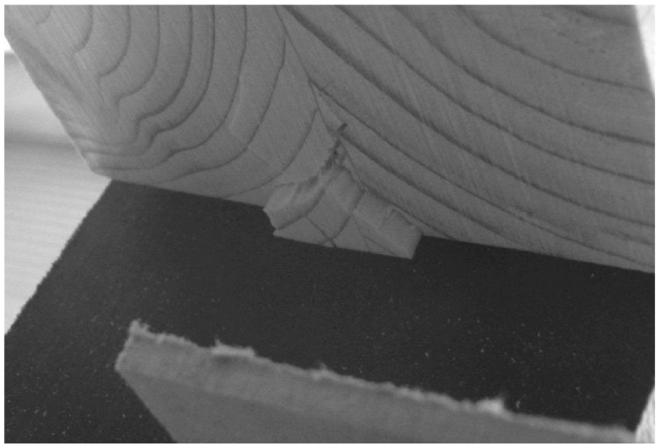

Figure 4. Shear wedge during the test

When the end distance of the connection provides sufficient resistance the three-hinge failure occurred to peg, Mode I shown in Figure 3, resulting ductile failure of connections. If the connections have insufficient end distance to lead to three-hinge failure in peg, a shear wedge occurred in the side members and the peg would fail in a single hinge, as Mode II in Figures 3 and 4. Unlike shear plug failure found in our previous work (Shanks *et al.* 2008), this kind of failure did not result in sudden drop in strength. On the contrary, the strength decreased gradually when the shear wedge occurred at the end of the connections. For the connections with only 1.5d end distance, Mode II failure occurred. Two of the six connections with 2.5d end distance failed in Mode II, the remaining failed in Mode I. Plywood failure occurred only when the plywood used had apparent natural defects. Only four in 96 connections failed in the plywood, one each in Series A and Series C, two in Series B. Failure mode observed in the plywood does not occur very often but it leads to brittle failure of connections, i.e. the strengths of the connections drop drastically. Such a failure mode is unfavourable in the perspective of structural safety as there is little warning of impending failure.

The Mode IV and V occurred only in the connections with multiple pegs. In the Mode IV, all the pegs in the connections failed in three-hinge failure. Mode V is where the peg closest to the end failed in single hinge with shear wedge and the rest of the pegs failed in three-hinge failure. The test results reveal that Mode II and IV occurred only when the end distance of base material in the connection is not larger than 3.5d; this phenomenon can be observed from both single and multiple pegs connections. The experimental results of connection tests are given in Table 2.

Table 2. Experimental results and failure mode

	Yield Strength		
Exp	**Mean (kN)**	**SD (kN)**	**Failure mode [1]**
A-15-1~A-15-6	4.386	0.260	II
A-25-1~ A-25-6	5.641	0.433	I, II
A-35-1~A-35-6	5.766	0.549	I, III
A-45-1~A-45-6	5.479	0.459	I
B-20-1~B-20-6	10.910	0.540	III, V
B-30-1~B-30-6	12.290	0.908	IV, V
B-40-1~B-40-6	12.537	0.617	III, IV
B-50-1~B-50-6	12.511	0.485	IV
C-20-1~C-20-6	10.939	1.341	IV
C-30-1~C-30-6	12.028	1.155	IV
C-40-1~C-40-6	12.740	0.980	IV
C-50-1~C-50-6	12.636	1.197	III, IV
D-20-1~C-20-6	14.65	2.851	IV
D-30-1~C-30-6	14.87	2.179	IV
E-20-1~E-20-6	18.26	3.734	IV
E-30-1~E-30-6	18.51	4.554	IV

1 Failure mode is depicted in Figure 3.

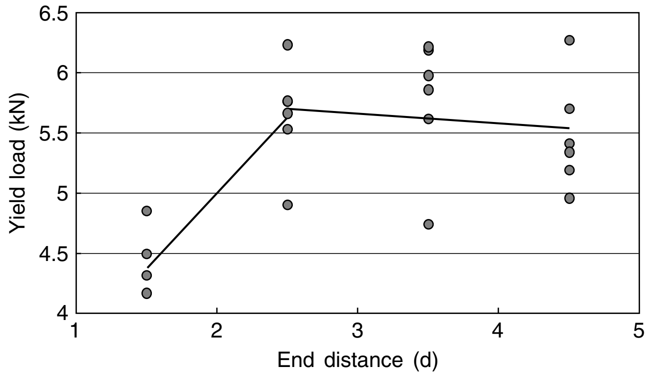

Figure 5. End distance versus yield strength of single peg connections

4. DISCUSSIONS

4.1. Minimum End Distance

If the end distance cannot provide sufficient shear area to resist the force which leads to plastic hinge failure in the peg, shear plug failure will occur in the connections. This usually results in brittle failure in connections (Shanks *et al.* 2008). Thus, in the design of timber joints, a minimum end distance is required to ensure a gradual, termed ductile failure of the connections, a desirable feature in connection design. EC5 prescribes the minimum end distance of 7d up to a maximum of 80 mm. This end distance is for steel pegs, which requires larger end distance to perform to a safe percentage of the full strength. The yield load versus the end distance of connections tested in this study is plotted in Figure 5. As expected, the curves reach a plateau when the end distances are sufficient to develop full joint strength. From Figure 5 one can learn that from this study the minimum end distance to ensure peg failure for the joints with spruce side members with plywood central member driven with oak peg is 2.5d. It should be noted that the desirable minimum end distance may be somewhere between 1.5 and 2.5d but not captured in this study which looked at 1.5d and 2.5d.

Notice that although shear wedge occurred in some connections with 2.5d end distance, it did not result in brittle failure for the test specimens presented herein. Hence 2.5d end distance is sufficient to lead to full performance of the connection from the perspective of yield load; however, to prevent occurrence of shear wedge, 3.5d is the recommended minimum end distance. Furthermore if it is desirable that a connection should be easily repairable after failure then 3.5d should be adopted to ensure peg failure rather than failure of the base material.

4.2. Minimum Spacing between Pegs

In addition to minimum end distance, sufficient spacing between pegs parallel to the grain can help to provide full capacity of adjacent pegs in the connections. EC5 prescribes the minimum spacing between pegs parallel to the grain for 5d. This large minimum spacing is undoubtedly sufficient but as discussed previously the EC5 spacing is for connections with steel pegs. When using timber pegs it will result in inefficient use of the connecting area. Figures 6(a) and (b) depict the relationship between yield load and parameter a_1 with end distance of 2.5d and 3.5d, respectively. From this figure one can learn that for connections with end distance of 2.5d and 3.5d, the minimum spacing between pegs parallel to the grain of 3d is sufficient to lead to full strength of the connections. As previously discussed and observing from the failures after the tests, shear wedge did not occur to the connection specimens tested with 3.5d end distance. Hence to exhibit full performance of connections, 3.5d end distance and 3d spacing between pegs parallel to the grain are recommended.

4.3. Stiffness and Strength of Connections

The stiffness and strength of connection are two important characteristics of a connection. To estimate the stiffness of the connection, the spring model, as shown in Figure 7, is used in this study to estimate the connection stiffness. Observing from the specimen after failure, the entire deformation of the connections was attributed from that of side members due to local bearing and pegs due to bending; as the plywood central

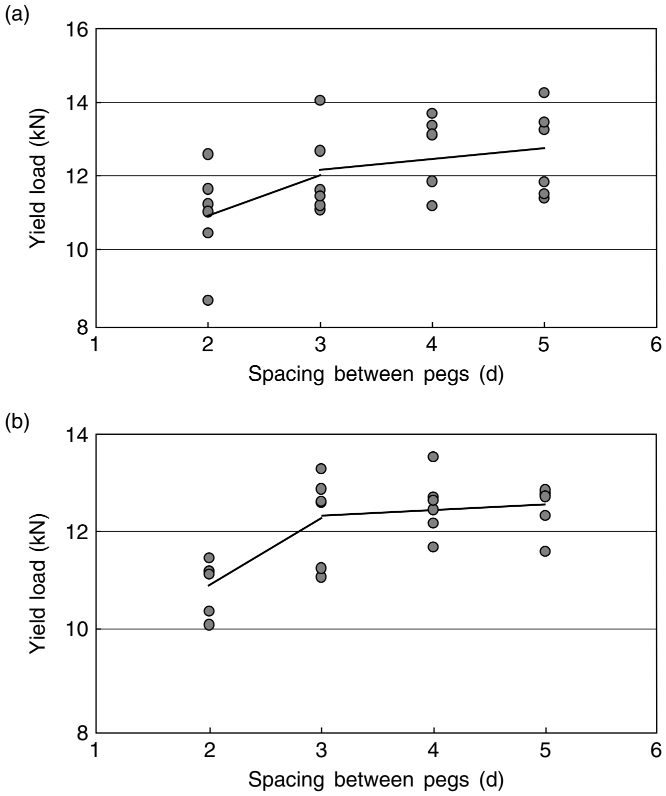

Figure 6. (a) Spacing between pegs versus yield strength of connections with a_{3t} of 2d; (b) Spacing between pegs versus yield strength of connections with a_{3t} of 3d

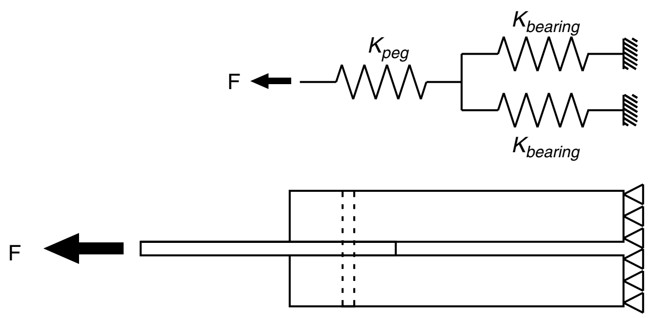

Figure 7. Spring model for estimating the stiffness of connections

member very often did not deform significantly. Hence for the connections that exhibit the full performance, if the bearing deformation of plywood can be neglected, the stiffness of the connection can be estimated as:

$$K_{connection} = \frac{2K_{peg} \times K_{bearing}}{2K_{bearing} + K_{peg}} \tag{1}$$

where K_{peg} and $K_{bearing}$ are stiffness respectively provided by the peg and that by side member under bearing.

Observation from the failed connections after the tests indicates that the average shear span of the peg that failed in Mode I was approximately 18 mm, similar to the thickness of the plywood as annotated in Figure 3. This implies the behaviour of the peg when the connection is subjected to tension force is similar to that of the fixed-fixed end bending test with span ratio of 1.14. Figure 8 demonstrates the span ratio versus peg stiffness obtained from peg bending tests, from which we can estimate the averaged peg stiffness contribution to the overall connection is about 7.03 kN/mm, obtained by linear interpolation from span ratios of 1 and 2; i.e. the average span stiffness of peg with span ratio of 1 is about 7.44 kN/mm, and is 4.54 kN/mm with span ratio of 2. As previously mentioned, the bearing strength and bearing stiffness of each specimen have been determined, hence we can estimate the stiffness of a connection by combining the bearing stiffness of the side members and averaged peg stiffness with span ratio of 1.14, i.e. 7.03 kN/mm, into Eqn 1. Figure 9 shows the comparison between estimated stiffness and that obtained from the test. Notice in Figure 9 only connections with pegs failed in three hinges were used for the comparison, which include connections with end distance of 3.5d and 4.5d and part of 2.5d. From Figure 9, linear relationship can be seen between estimated and experimental results. The errors might be

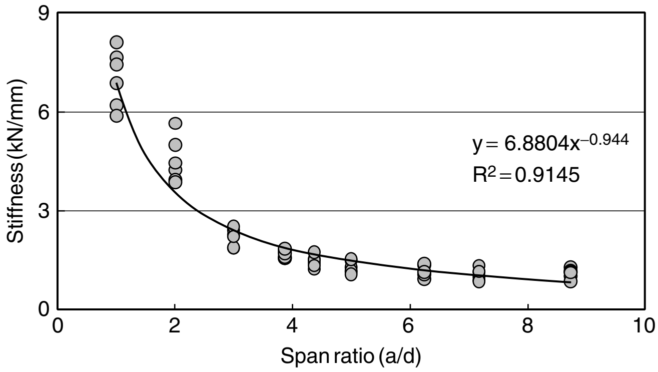

Figure 8. Shear span ratio versus stiffness of pegs

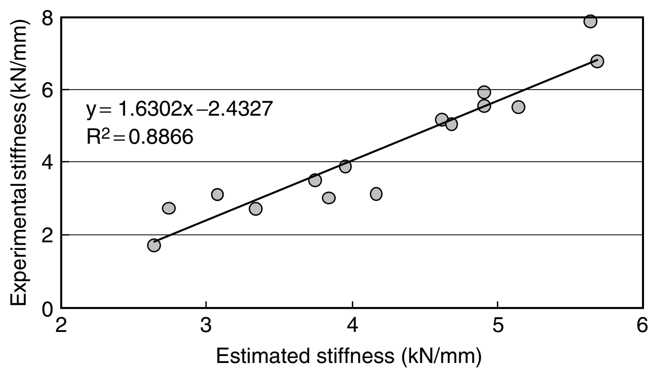

Figure 9. Comparison of estimated and experimental stiffness

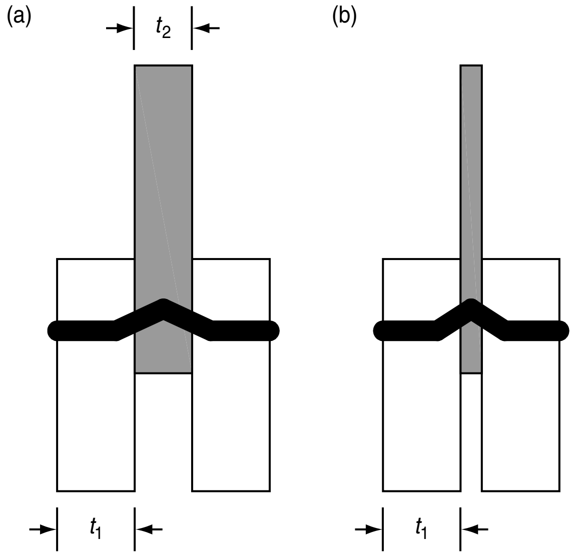

Figure 10. Connections with peg fail in three hinges: (a) timber-to-timber; (b) steel-to-timber

attributed to the variation in peg material, as the stiffness of the pegs is assumed uniformly at 7.03 kN/mm. Also the friction between pegs and side members is neglected and the bearing deformation of the plywood is not considered. Generally, however, the prediction is good.

EC5 proposes two formulas to calculate the characteristic load-carrying capacity of dowel-type connections with three hinge peg failure, one for timber-to-timber connections and another for steel-to-timber connections as shown in Figure 10. Eqn 2 is proposed by EC5 for timber-to-timber connections aforementioned:

$$F_{v,\,Rk} = 1.15 \cdot \sqrt{\frac{2\beta}{1+\beta}} \cdot \sqrt{2M_{y,\,Rk} \cdot f_{h,\,1,\,k} \cdot d} \tag{2}$$

where $F_{v,\,Rk}$ represents characteristic load-carrying capacity per shear plane per fastener; $M_{y,\,Rk}$ and $f_{h,\,1,\,k}$ stand for characteristic yield moment capacity of peg and characteristic embedment strength of side members, respectively. The diameter of peg is termed d in the equation. β is the ratio between the embedment strengths of the members and can be calculated as:

$$\beta = \frac{f_{h,2,k}}{f_{h,1,k}} \tag{3}$$

$f_{h,\,2,\,k}$ stands for characteristic embedment strength of central members.

For the formula proposed by EC5 to estimate the characteristic load-carrying capacity of steel-to-timber dowel connections with three hinge peg failure as shown in Figure 10(b) is given as:

$$F_{v,\,Rk} = 2.3\sqrt{M_{y,\,Rk} \cdot f_{h,\,2,\,k} \cdot d} \tag{4}$$

Notice that the connections investigated in this study have two shear planes, thus Eqns 2 and 4 should be multipled by 2 when estimating the capacity of the connections. Based on the material test the characteristic yield moment capacity of pegs ($M_{y,\,Rk}$) is 22.09 kN-mm, the characteristic embedment strength of side members ($f_{h,\,2,\,k}$) and central members ($f_{h,\,1,\,k}$) is 16.45 N/mm^2 and 50.24 N/mm^2, respectively. In this study, British Standard EN 14358 was used to determine the characteristic value. Substituting above values into Eqns 2 to 4 yields connection capacity of 2.41 kN by Eqn 2 and 5.50 kN by Eqn 4. If we multiple the above value by 2 as discussed, the capacity for timber-to-timber connection is 4.81 kN whilst it is 11.09 kN for steel-to-timber connection. The result calculated from Eqn 4 is higher than the test values, and Figure 11 shows the comparison between estimated capacity calculated from Eqn 2 and the test results. One can see that except for connections with plywood failure (Mode III) and shear wedge (Mode II), the estimated capacity timber-to-timber connection capacity calculated by Eqn 2 proposed by EC5 tends to underestimate the capacity at reasonable range with only one exception (4.74 kN-mm) in 16 specimens.

4.4. The Effective Number of Fasteners Parallel to the Grain

When analysing the load carrying capacity of a connection with multiple pegs parallel to the grain predicting the performance by multiplying the performance on a single peg by the number of pegs does not represent the true behaviour in many cases. Hence it

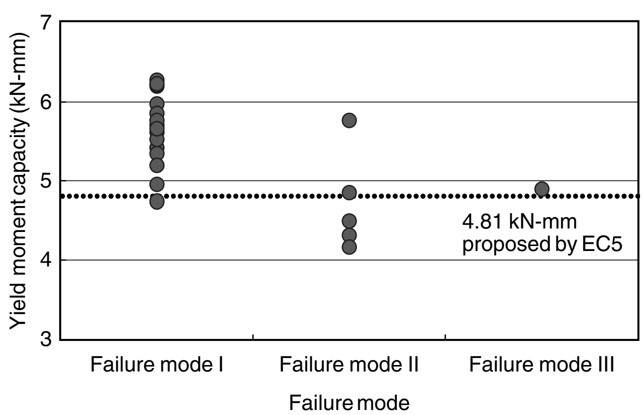

Figure 11. Comparison of experimental results with result estimated by EC 5

is widespread practice to consider the effective number of fasteners, termed n_{ef}, in design code, such as EC5. The effective number proposed by EC5 can be expressed as:

$$n_{ef} = \min\begin{cases} n \\ n^{0.9} \cdot \sqrt[4]{\dfrac{a_1}{13d}} \end{cases} \quad (5)$$

where a_1 is the spacing between dowels along the grain direction; d is the dowel diameter, and n is the number of dowels in the grain direction. Hence for one row of fasteners parallel to the grain direction, the characteristic load carrying capacity should be taken as:

$$F_{v,ef,Rk} = n_{ef} \cdot F_{v,Rk} \quad (6)$$

If the spacing between pegs parallel to the grain, a_1, is assumed as 5d, according to EC5 the relation between number of pegs (n) and effective number (n_{ef}) proposed by EC5 can be expressed in Figure 12, in which the relation appears to be nearly linear. The comparison between experimental load-carrying capacities of connections included in our experimental programme and estimated value calculated from Eqn 6 is given in Figure 13. As expected, the estimated value proposed by EC5 tends to underestimate the experimental value. However, note that the estimated value is 44–84% of the experimental results, which appears to significantly underestimate the connection capacity and will result in inefficiency of the connections. This study proposes a modified effective number which can be expressed as:

$$n_{ef,\,\mathrm{mod}} = n^{0.8} \quad (7)$$

where n is the number of pegs in the grain direction. Then comparison between experimental results with load carrying capacity calculated using modified

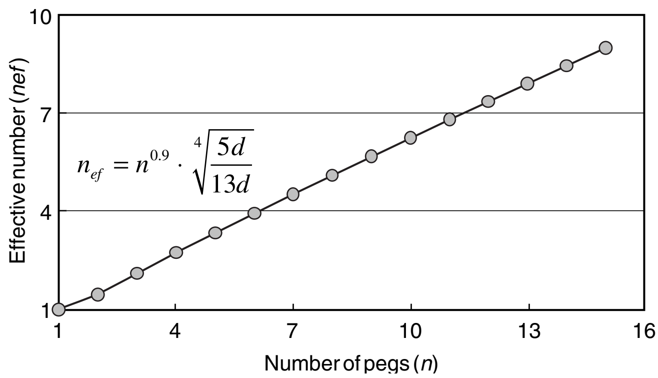

Figure 12. Effective number proposed by EC5 with a_1 equals to 5d

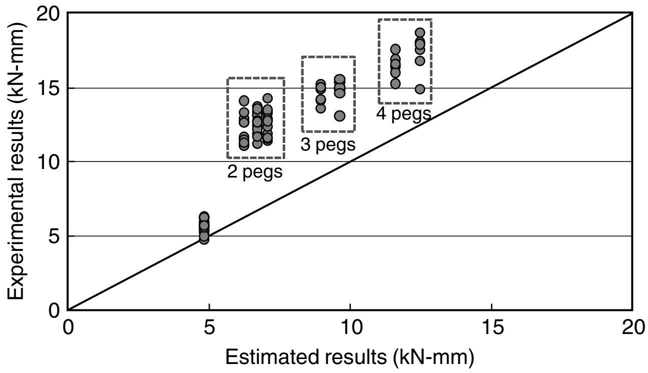

Figure 13. Comparison between experimental results with estimated results calculated by EC5

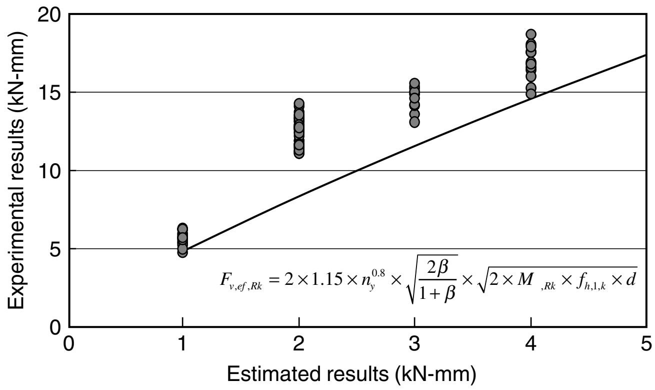

Figure 14. Comparison of experimental results with estimated results calculated considering the modified effective number

effective number is illustrated in Figure 14. It appears that the modified evaluation method still tends to underestimate the experimental result, which is conservative in practice; but the estimated value is around 60–98% of experimental results.

5. CONCLUSIONS

In this study, a total of 96 double-shear connection specimens connected with plywood and Oak pegs were tested in tension, loading the pegs in double shear, to explore the minimum end distance and spacing between pegs parallel to the grain. A new failure mode, named shear wedge, was found in this study, which occurs when the connection did not provide sufficient end distance. Connections do not exhibit brittle failure when shear wedges occur; instead, the strength decreases gradually when it occurs. The test results show that this type of connection requires minimum end distance of 2.5d to exhibit full performance, but that 3.5d minimum end distance is required to prevent shear wedge failure. A minimum spacing between pegs parallel to the grain of 3d is required to exhibit full performance in connection and leads to three hinge failure in pegs.

A spring model is proposed in this study to estimate the stiffness of the connection with satisfactory agreement. Using the formula proposed by EC5 to calculate the characteristic load-carrying capacity of connections provides reasonable results. A new method to evaluate the effective number was proposed in this study to consider the load-carrying capacity of connections with multiple pegs in a row. The comparison between experimental results with values calculated using modified effective number appears to be acceptably conservative. More tests should be carried out to investigate the minimum edge distance and spacing between rows perpendicular to the grain so that all the geometrical requirements for plywood flitched connections with non-metallic fasteners can be determined.

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