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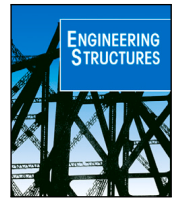
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# Stiffness and slip in multi-dowel timber connections with slotted-in steel plates

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## ABSTRACT

Large multi-dowel connections can provide the strength and ductility required for large, highly-loaded timber structures, but their slip under load is not well understood. This is an important gap in knowledge, because accumulated local displacements at connections represent a large part of the deformation of a timber structure. The empirical relationships used in design codes commonly scale a single-dowel stiffness by the number of dowels, so do not capture the dowel interaction effects of the multi-dowel connections used in larger structures. We present the results of an experimental test series, elastic model and probabilistic numerical analysis investigating the development of stiffness in multi-dowel timber connections with slotted-in steel plates. Novel test methods record the development of stiffness due to each individual connector to show that the stiffness of the complete connection is not proportional to the number of dowels. An elastic stress-function model shows that this is partly due to interaction of the stress field around the dowels. For the first time, this work quantitatively considers the influence of misalignment of dowels due to manufacturing tolerances, and it is shown that this may greatly reduce the overall stiffness of a multi-dowel connection. The test series is used to validate a probabilistic model of this misalignment for the stiffness of such a connection. The model incorporates the nonlinear stiffness and hole opening observed in single-dowel connections to predict the behaviour of the group. The study shows that the random misalignment of dowels in multi-dowel connections reduces the range of displacements over which the connection displays zero stiffness slightly, but that this zone is not eliminated as a result of irreversible hole opening under load, even for a connection with 35 dowels and three steel plates. We conclude that two parameters are important for the design of these connections: the unload-reload stiffness and the zero-stiffness region measured between the zero load intercept of the unload-reload linear fit. With these, a reasonable estimate can be made of the displacement at any serviceability load level in either tension or compression.

## 1. Introduction

Timber connections with steel dowels and slotted-in (flitch) plates provide the high strength and ductility required in large buildings and bridges [1,2]. Single-dowel connections, or multi-dowel connections with a group of perfectly-centred dowels, develop a slip due to opening of the hole in the timber and the oversizing of the hole in the steel plate [3,4]. This would give the connection zero stiffness, or looseness under near-zero loads. The random misalignment of the dowels in a group as a result of tolerances in manufacture and construction can be expected to mitigate this effect. Jorissen [5] discusses the effect of

misalignment on the distribution of load in a multi-dowel connection and comments on its potential effect on connection strength, particularly in the case of brittle failure.

The deformation of connections is important for the design of timber structures for both static deflection and vibration. The 14-storey Treet building in Norway [2] has more than 200 joints in the trusswork, which have a significant effect on the deflection and vibration of the whole building. Mam et al. [6] show that the semi-rigid behaviour of joints in timber truss structures affects their optimum geometry

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and the design of individual members. Floors with dowelled connections will also depend on those connections for stiffness and vibration properties [7].

The force–displacement behaviour in a single-dowel connection is highly non-linear. Reynolds et al. [3] show substantial irreversible deformation, even under loads approximately 20% of the failure load. The result of this is that, as shown by Reynolds et al. [4], the stiffness of a connection is only predicted well by an elastic model for repeated small-amplitude one-sided loading, where the load does not return close to zero (in the tests by Reynolds et al. [4], the cyclic component is approximately 20% of the mean).

Dorn et al.'s [8] experimentally-calibrated finite element model suggests that plastic behaviour in steel and timber occur at even at serviceability loads, and flexible, frictional contact across their interface also leads to irreversible deformation at these load levels. This model, along with the associated experiments shows: the gradual take-up of load; the difference between the initial stiffness and the stiffness under unload and reload; and the residual deformation even after low initial loading.

Reynolds et al. [3,4] find the residual deformation after loading up to 40% of the expected failure load to be approximately 0.2 mm for a 12 mm dowel in laboratory specimens. Importantly, the condition of the surface of the wood in contact with the dowel appears to have a strong effect on this residual deformation [8], meaning that the manufacturing processes used to make the specimens are important. For the present study, the specimens were made by a commercial manufacturer using Computer Numerically Controlled (CNC) drilling, to achieve a quality that is representative of that which would be expected in construction.

Despite the non-linear connection behaviour, it is common to use an equivalent elastic stiffness in design; either by incorporating semi-rigid joints into a model, or by reducing the stiffness of the members to allow for joint deformation (e.g. [2]).

Eurocode 5 design guidance [9] gives an elastic stiffness for a single shear plane of an individual connector,  $K_{ser}$ , which is multiplied by the number of connectors and the number of shear planes for each to obtain the stiffness of the connection. It has been widely reported that this representation is not sufficiently accurate for modern timber structures, and does not sufficiently capture the properties of the connection [10–12].

Seeking a more physically representative design model of the connection behaviour, a beam-on-elastic-foundation model has been widely proposed. The foundation modulus can then be derived by an elastic [4,13–17] or nonlinear [18,19] model of the surrounding timber, or experimentally [12].

The *group effect* in timber connections [20] expresses the idea that a group of connectors does not generally behave like a linear combination of the responses of an individual connector. Most work on the group effect focuses on the strength of connections (e.g. [21–25]), with limited commentary on the stiffness of such connections. Hochreiner et al.'s work [22] measures the strain fields extending into the timber around the dowels, showing the potential for them to overlap and interact with each other, pointing towards the possibility of a group effect on the stiffness of the connections.

This paper investigates the nature of the force–displacement diagram for connections in softwood and hardwood, in two different dowel sizes. Group effects are investigated by gradually increasing the number of dowels in the connection. Cycles of load are applied to explore the force–displacement behaviour in detail and eventually suggest an appropriate simplified behaviour to assume in design. The behaviour is modelled by an elastic stress function model, to capture the effect of interaction of stress fields around the dowels and a Monte Carlo simulation for the effect of dowel misalignment on stiffness.

## 2. Materials and methods

### 2.1. Engineered wood products

Tests were carried out on two types of engineered timber made from two species of wood: Glued-laminated (glulam) timber specimens were made from ‘whitewood’, a term encompassing a group of northern European softwood species, including Norway spruce (*Picea abies*) and silver fir (*Abies alba*), used interchangeably in engineered wood products; Laminated Veneer Lumber (LVL) specimens were made from European beech (*Fagus sylvatica*), under the product name BauBuche, by Pollmeier GmbH. The glulam specimens are hereafter referred to as the “softwood” specimens, and the LVL specimens as “hardwood”. Moisture contents were measured using the oven dry method to be 11.5% for the softwood and 7.5% for the hardwood at the time of testing. All specimens were cut and drilled using contemporary computer numerical control (CNC) manufacturing techniques by Hess Timber GmbH. As a result of this, tolerances and dowel-hole misalignment were likely to be representative of modern timber construction.

The specimens are shown in Fig. 1. Small and medium specimens with rows of dowels were used to investigate the influence of each additional connector as they were added to the specimen one by one. Larger specimens were used to observe the stiffness behaviour in a complete full-size connection of sufficient capacity for a large timber structure. The small and medium specimens had groups of five steel dowels in a line at each end. The spacings between dowels and the edge distances in the 5 + 5 dowel specimens are the minimum recommended in Eurocode 5 [9]. These dowels were added one by one to each specimen, starting with those nearest to the end of the specimen, with the loading protocol in Fig. 3 applied after the addition of each dowel. This enabled the behaviour of each dowel to be characterised in each direction under initial loading and an unload reload cycle. Large specimens had a group of 35 dowels passing through three steel plates at each end of the specimen.

### 2.2. Verification of geometry

The space between dowel centres was measured in each of the manufactured specimens and used to calculate a standard deviation of hole position, as a measure of the misalignment of the dowels. The centre positions were estimated by fitting circles to each dowel hole using Matlab®'s *imfindcircles()* function, and verified by physical measurement with calipers.

These measurements relied on identifying the edges of the holes accurately, either physically or in the images, and since the edges had some roughness, this will have been a source of error in the estimated centre positions. The error induced by this would be expected to lead to an overestimate of the standard deviation of hole position.

These methods were used to measure the distance between dowels along the centreline of the dowel row. The spacing between the dowels  $s$  can be thought of as the difference between two location coordinates  $y_1$  and  $y_2$  for each of the dowels. If the standard deviations of those coordinates are equal, and equal to  $\mu_y$ , then this can be related to the standard deviation of the spacing  $\mu_s$  by Eq. (1). Thus the standard deviation of position  $\mu_y$  was calculated from the measurements for further modelling.

$$\mu_s = \sqrt{\mu_y^2 + \mu_y^2} = \sqrt{2}\mu_y \quad (1)$$

### 2.3. Test procedure

The loading protocol is based on that from EN 26891 [26], modified to include a load reversal and to test both tension and compression in the specimen. The cycles of load go from 40% to 10% of the estimated capacity of the connection. This was done to comply with the code and compare with previous research, but also is a reasonable representation

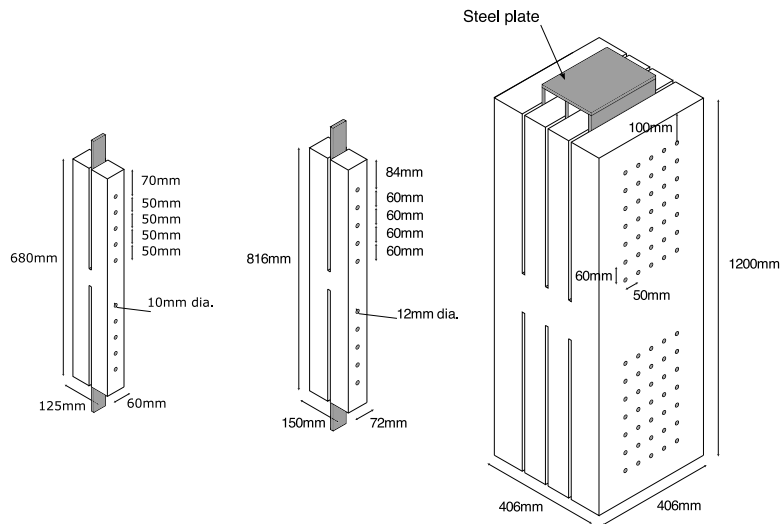


Fig. 1. Small, medium and large test specimens.

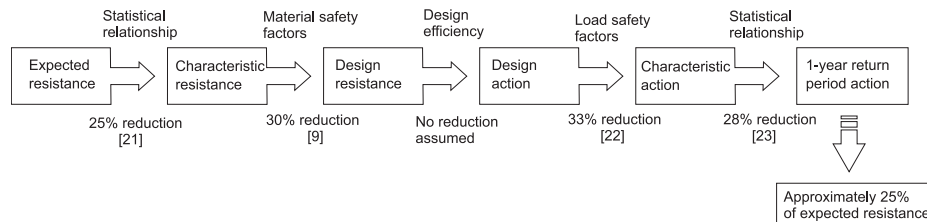


Fig. 2. Comparison of expected load capacity of a timber connection to predicted 1-year return period load [9,27–29].

of the load that a connection would be expected to see in normal service, taking into account the statistical relationships and partial factors used in design.

As shown in Fig. 2, using the example of design for wind load according to the Eurocodes, the 1-year return period loading is approximately 25% of the expected load capacity of a connection, calculated using the average density of the material, as in this case. This calculation assumes  $\gamma_M = 1.3$  and  $k_{mod} = 0.9$  according to Eurocode 5 [9]. This is at the centre of the 10% to 40% range of the load cycle, and therefore the load cycle would seem to cover an appropriate range for serviceability loads.

The maximum estimated load,  $F_{max,est}$ , was calculated for the full complement of five dowels, allowing for the group effect on strength by using the effective number of dowels from Eurocode 5 [9] and then divided by five to give the estimated load on the first dowel. The load on the connection with two dowels was then double this, and so on. This meant that, assuming load to be shared equally between each dowel in a group, all tests would see the same peak load per dowel. This was considered important since a dowel stiffness is substantially different under first loading than it is under unload-reload, while the behaviour under repeated unload-reload cycles is relatively consistent [3]. Fig. 3 shows the loading sequence used in the 5 + 5 dowel tests.

The test matrix is summarised in Table 1. This results in a total of 100 tests using the loading sequence in Fig. 3, plus two tests on the large 35-dowel specimens with three steel plates and three rows of 7 dowels. The large specimens were tested in compression only, with any development of slack identified as a residual displacement at zero load.

Tests using 10 mm and 12 mm dowels investigated the influence of dowel diameter. Since manufacturing tolerances are typically independent of dowel diameter, the oversize of the hole in the steel plate is larger as a proportion of the dowel diameter for the smaller dowels. This leads to a difference in the effect of this oversizing on the resulting slip. The test with 35 dowels introduced two new influences: multiple

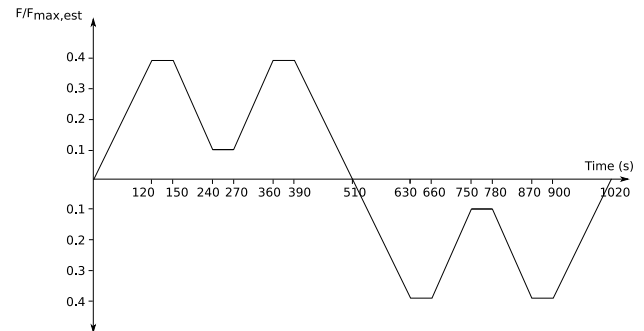


Fig. 3. Loading sequence.

Table 1

Test matrix.

Specimen size	Material	Dowel diameter	Number
Small (1 + 1 dowels) to (5 + 5 dowels)	Softwood Glulam	10 mm	5 × 5
	Hardwood LVL	10 mm	5 × 5
Medium (1 + 1 dowels) to (5 + 5 dowels)	Softwood Glulam	12 mm	5 × 5
	Hardwood LVL	12 mm	5 × 5
Large (35 + 35 dowels)	Softwood Glulam	12 mm	1
	Hardwood LVL	12 mm	1

rows of dowels, and multiple slotted-in plates. These compound the effect of construction tolerances, meaning that substantial force was required to install the dowels. The assembly of these specimens required a rotary hammer to be used, rather than the mallet used in the smaller specimens. It seems likely that internal forces will develop due to the deformation of dowels to accommodate inaccuracies in the hole locations around the steel plates.

CNC manufacture by a commercial manufacturer of timber structural components ensured that both the tolerance of manufacture and the nature of the surface of the drilled hole were representative of those which would be expected in real structures.

## 2.4. Numerical analysis

### 2.4.1. Elastic displacement field

The elastic distribution of stress and strain in the material around the dowel can be modelled through a stress function. For timber, an orthotropic material, the complex stress function developed by Lekhnitskii [30] is appropriate, and this is further developed by Hyer et al. [31] to deal with the friction and contact stresses around the edge of the hole. Reynolds et al. [4] show that this formulation can be used to predict the elastic foundation stiffness for a connection by superposition of the solution shifted and rotated in space to represent each individual connector. In this, the effect of the penetrations for other dowels is neglected. The foundation stiffness provided by the timber can then be used in a beam-on-elastic-foundation model to predict the stiffness of the connection as a whole.

In this study, the complex stress function is used to model the effect of adding connectors on the elastic stiffness of a multi-dowel connection, since each connector interacts with the displacement field of the others around it. The small and medium specimens were modelled by this method with 1 + 1 to 5 + 5 dowels.

The stress function model predicts the elastic component of the deformation of the material around the dowel under load. It has been shown [4,32] that this can be used as the foundation modulus in a beam on elastic foundation model to predict the stiffness of the connection using standard equations, such as given by Pikey [33]. Reynolds et al. [4] show that the elastic model is an accurate prediction of the connection stiffness under unload-reload when the change in force is small compared to the peak force, in that case when the R-ratio ( $F_{max}/F_{min}$ ) is equal to 1.2. When the R-ratio was higher, non-linear behaviour at low loads reduced the stiffness. In the present study, the R-ratio for the unload-reload stiffness is 4 and thus the elastic model would be expected to overestimate the true stiffness.

### 2.4.2. Monte-Carlo simulation for dowel misalignment

In order to investigate the effect of the random misalignment of dowels due to construction tolerances, a Monte Carlo simulation was used. The relationship between the increase in the zero-stiffness region due to irreversible deformation in the timber and its reduction due to misalignment of dowels were both included in the model. The force–displacement response of a dowel was represented by two elastic regions (one for compression and one for tension), a plastic zone above the predicted strength, and a zero-stiffness region, as shown for “Dowel 1” in Fig. 4.

The position of each dowel in the hole was modelled by a single coordinate. That is, it was assumed that the offset of the dowel in the hole could be modelled by a displacement, and the force in that dowel could be calculated using the assumed force–displacement response.

A Monte-Carlo simulation was carried out using MATLAB®, representing the initial coordinate of each dowel  $n$  in relation to Dowel 1 by a normal distribution, and generating the misalignment distance of each dowel for each realisation as a set of pseudo-random numbers from that distribution. The simplified force–displacement response for each dowel  $n$  was then offset by a displacement representing the misalignment of that dowel position, as shown in Fig. 4. The force at a given displacement for a connection with  $N$  dowels was then calculated as the sum of the force in every dowel  $n = 1 : N$  at that displacement. 1000 realisations were then used to find the mean, 5th percentile and 95th percentile response of the  $N$  dowel connection.

On this basis, the force in the connection for each realisation was calculated for a set of displacements ranging from –2mm to 2 mm, which covers the elastic region, and sufficient of the post-yield region to describe the overall behaviour. The statistical distribution of those forces, or alternatively the stiffness at each point of the force–displacement curve for each realisation, was then calculated.

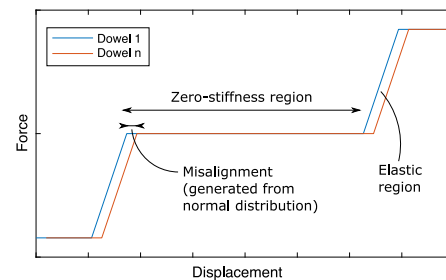


Fig. 4. Idealised response of a dowel, and the response of dowel  $n$  once the randomly-generated offset is added.

## 2.5. Factors which further reduce stiffness

Other factors further reduce the stiffness of the connection. One is that, as shown by Reynolds et al. [4], the stiffness of the connection only approaches that predicted by an elastic model for small oscillations of the load around the mean. The load cycle in these tests, between 40% and 10% of the estimated failure load, would be expected to have a reduced stiffness. This would be expected to be a local effect, driven by nonlinear behaviour close to the dowel hole, and so would not be expected to be affected by the number of dowels in the connection.

The misalignment of dowels in the direction perpendicular to the applied load would also be expected to reduce their stiffness as they load the hole edge obliquely. The specimen would be expected to rotate to some equilibrium position based on the offsets of each dowel. This effect could increase with the number of dowels, as dowels far from the centroid of the group would be expected to define the equilibrium rotation and dowels near the centroid may be severely misaligned. It is beyond the scope of this study to model the above effects.

## 3. Results and discussion

### 3.1. Numerical analysis

#### 3.1.1. Elastic displacement field

Fig. 5 shows the modelled displacement in the direction of loading along the centreline of a line of dowels. The plot shows the displacement of the timber for a single pair of dowels being pushed towards one another at a distance of 56 times their diameter centre to centre. This was the first test carried out on each specimen. The displacement of the dowel is equal to the displacement of the timber where they are in contact, equal to 0.58 mm/kN in this case.

The displacement along the line A-A in Fig. 5 is plotted in Fig. 6. Fig. 6 also shows the displacement in the timber for two groups of five dowels being pushed towards one another, with a spacing of 5 times the dowel diameter between their centres. Since each dowel in the group passes through the same steel plate, and the deformation of the plate is assumed to be small, the five dowels are constrained to displace by the same amount.

It can be seen in Fig. 5 that the elastic deformation in the timber is not localised around the dowel, and that there is significant displacement of the timber at the location of the adjacent dowel. The figure shows the displacement field due to a single pair of dowels, and at the location of the adjacent dowel, five hole diameters away, the displacement of the material is still approximately 50% of that at the hole edge. When an additional dowel is added at that location and moves to the same displacement as the first, it does not, therefore, generate the same force. As a result, the displacement per unit force of the five-dowel group (0.18 mm/kN) is substantially more than one fifth of the displacement of the single dowel, which would be 0.11 mm/kN. This effect can be represented as an effective number of dowels, given by the stiffness of the multi-dowel connection divided by the stiffness

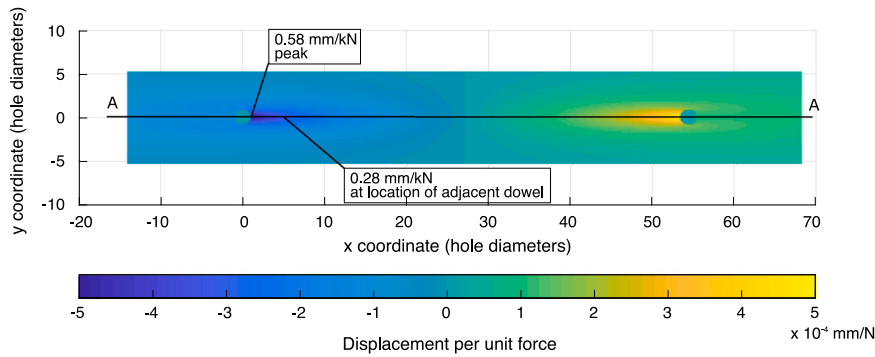


Fig. 5. Modelled elastic displacement in the direction of load application along a line through the centre of the dowel holes.

Table 2

Effective number of dowels based on elastic stress fields for each specimen type.

Number of dowels	1	2	3	4	5	7 <sup>a</sup>
Softwood	1	1.49	1.91	2.40	3.07	3.24
Hardwood	1	1.48	1.90	2.38	3.05	3.19

<sup>a</sup>The seven-dowel model is based on the geometry of the large specimens, all others apply to the small and medium specimens.

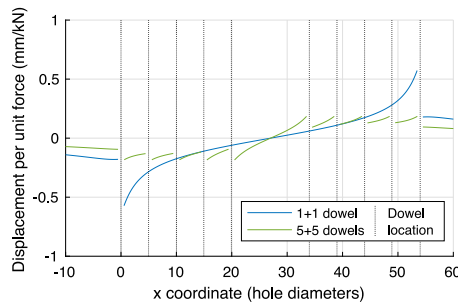


Fig. 6. Modelled elastic displacement in the direction of load application along a line through the centre of the dowel holes, line A-A in Fig. 5.

of the single dowel connection (see Table 2). It should be noted that these predicted stiffnesses do not change as the connection is scaled (as it is between the small and medium specimens). Based on the beam-on-elastic-foundation model, the elastic components of stiffness for the single dowel specimens are predicted to be 72 kN/mm for the 12 mm dowel in softwood, 90 kN/mm for the 12 mm dowel in hardwood, 60 kN/mm for the 10 mm dowel in softwood and 75 kN/mm for the 10 mm dowel in hardwood.

### 3.1.2. Monte Carlo simulation for dowel misalignment

Table 3 shows the standard deviation of the measured spacing between dowel hole centres in the along-grain direction for each specimen type. The Monte-Carlo simulation was used to investigate the effect of the measured dowel misalignment on the force–displacement response of the connections.

The standard deviation appears to be the result of random variation, rather than any consistent variation with size or material. For this reason, a standard deviation of hole position of 0.15 mm was used for all calculations.

There was no substantial difference in the spread of dowel positions on either side of each specimen, which suggests that the holes were drilled sufficiently straight that any deviation in position on the exit side was small compared with the error in placement of the hole on the entry side.

For the model, the idealised response of each dowel has a zero-stiffness region equal to the mean from the single-dowel tests, shown

Table 3

Dowel misalignment, expressed as standard deviation of measured dowel positions for all dowel holes in each specimen type.

	Standard deviation of dowel centre position
Small softwood	0.14 mm
Small hardwood	0.19 mm
Medium softwood	0.17 mm
Medium hardwood	0.13 mm
Large softwood	0.11 mm
Large hardwood	0.15 mm

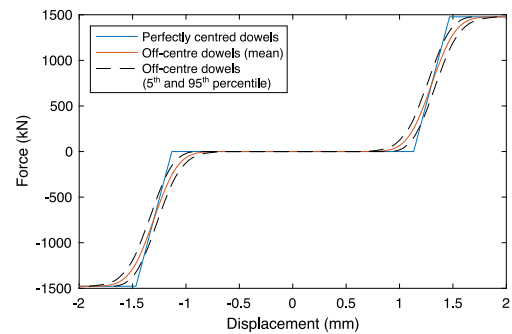


Fig. 7. The modelled force–displacement response of a connection with perfectly centred dowels, and the modelled mean, 5th and 95th percentile response of a 35-dowel connection with randomly offset dowels.

in Fig. 10, and beyond the zero-stiffness region its response is elastic, with using the mean stiffness from the single-dowel tests in Fig. 9. So, for example, the 12 mm dowels in softwood have a zero-stiffness range of 2.26 mm and an elastic stiffness of 20.9 kN/mm. These idealised responses are then combined and offset according to a normal distribution with a mean of zero and standard deviation of 0.15 mm.

Fig. 7 shows both the idealised response of the perfectly centred dowels used in the model, and the effect of dowel misalignment on the mean response of a 35-dowel connection. It can be seen that, even with 35 dowels, the reduction in the zero-stiffness slip area is small, but that the stiffness of the connection is significantly affected. In this case, 40% of the estimated failure load is 591 kN, so the 10%/40% stiffness is significantly affected by dowel misalignment.

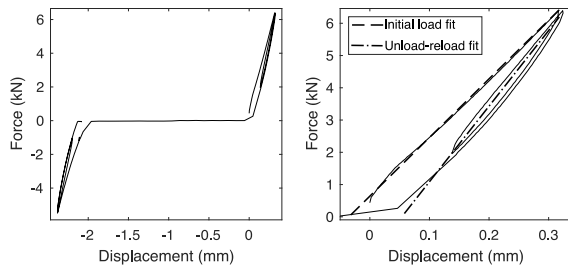
The effect of misalignment on stiffness can be quantified by dividing the modelled 10%/40% stiffness of the multiple-dowel connection by the 10%/40% stiffness of a single dowel on which the model is based. This ratio is described as the “Effective number of dowels”, and the results are shown in Table 4 for the range of specimens tested in this study.

**Table 4**

Effective number of dowels based on dowel misalignment for each specimen type (Mean over 1000 realisations).

Number of dowels	1	2	3	4	5	105 <sup>a</sup>
10 mm Softwood	1	1.41	1.90	2.37	2.84	–
10 mm Hardwood	1	1.40	1.84	2.31	2.79	–
12 mm Softwood	1	1.51	2.02	2.63	3.21	64.3
12 mm Hardwood	1	1.45	1.95	2.50	3.00	60.5

<sup>a</sup>The large connections have 35 dowels which pass through three steel plates each.



**Fig. 8.** Measured force–displacement response of a softwood connection (left) with a single 12 mm dowel, and a detail of the response (right) showing fits of the initial loading, and the unload-reload portion of the tensile loading curve.

### 3.2. Experimental work

For each specimen, a force–displacement diagram for the tension and compression loading was recorded for each of the five tests, as the dowels are added one by one. Fig. 8 shows that force–displacement diagram for the test on a softwood connection with a single 12 mm dowel. The zero-stiffness region is 2 mm, due to the 1 mm oversize of the holes in the steel plates at each end of the specimen. The irreversible deformation in each dowel after one cycle of load acts to open up the hole in the timber, and this adds to the oversize of the hole in the steel plate to give the total zero-stiffness slip in the connection. After the compression and tension loading, the zero-stiffness region increased to 2.26 mm, as a result of irreversible deformation of the hole due to embedment of the dowel in the timber.

The right hand plot in Fig. 8 shows the lines fitted to the initial loading and unload-reload curves for the tensile loading region of the force–displacement curve in the left hand plot. Once these lines were fitted to both tensile and compressive cycles of load, it was possible to define parameters to characterise the behaviour of the connection once it has seen a tensile and compressive load of 40% of its estimated failure load: the unload-reload stiffness in tension and compression, and the zero-stiffness region. The change in the value of these parameters as more dowels are added allows the group-effect of dowels on stiffness to be assessed for this dowel-group geometry.

If the designer is concerned with the total deformation of the structure from an initial unloaded condition, the zero-stiffness region will have an effect. For this, the loading history is important, but one might conservatively assume that the structure has at some time been loaded to 40% of its predicted failure load, in which case a designer could assume an initial slip equal to half of the zero-stiffness region defined here, between the intercepts of the unload reload stiffness fit, and then add an elastic displacement based on the unload-reload curve. The following parameters will therefore be presented in this paper: the unload-reload stiffness and the zero-stiffness region.

#### 3.2.1. Small and medium specimens

Fig. 9 shows the measured gradient of the unload-reload curve for each specimen, using the fitted lines illustrated in Fig. 8. The stiffness of the connection increases with the addition of each dowel, but it does not increase in proportion with the number of dowels for either

specimen type. For example, the mean of the unload-reload stiffness of a single-dowel connection with a 12 mm dowel is 20.9 kN/mm. For five dowels on each of the specimen, the mean is 54.0 kN/mm, which could be expressed as an effective number of dowels of 2.6. For the 10 mm dowels, a single-dowel specimen gives a stiffness of 17.2 kN/mm, and the five-dowel specimen 40.5 kN/mm, giving an effective number of dowels of 2.4. The results for each individual specimen, plotted in grey, show that in general, a specimen stiffer with one dowel is stiffer with two, three, four and five dowels, although the evolution of each single specimen does not always follow the trend of the evolution of the mean. There are some examples where a specimen is made less stiff by the addition of a dowel.

For the softwood, with density 378 kg/m<sup>3</sup>,  $K_{ser}$  according to Eurocode 5 is 3.9 kN/mm for the 12 mm dowels and 3.2 kN/mm for the 10 mm dowels. These connections have two shear planes and the stiffness is doubled for a steel-to-timber connection, so the connection stiffness would be predicted to be equal to  $4 \times K_{ser}$ . Each specimen has two connections in series, therefore the specimen stiffness will be  $2 \times K_{ser}$ . If Eurocode 5 [9] uses the same definition of slip modulus as EN 26891 [26], then the slip modulus  $K_{ser}$  would be designed to represent the initial loading curve, neglecting any initial low stiffness at loads lower than 10% of the expected ultimate load. The Eurocode prediction of 6.4 kN/mm is therefore inaccurate in this case: the initial loading stiffness has a mean of 15.5 kN/mm for the 12 mm single-dowel specimen.

Fig. 9 also shows the prediction of stiffness of the multi-dowel connections, based on the experimental single-dowel connection stiffness, using the ratios from Table 4. This shows that while some of the reduction in stiffness of the connection can be accounted for this way, it does not allow for the whole effect, particularly for the four- and five-dowel connections, and particularly in the hardwood specimens. The interaction of the stress fields around the dowels, described in Section 2.4.1, will contribute to this reduction, but since the elastic model severely overpredicts the stiffness of the connection in this case, it will not be a good quantitative indicator of the reduction.

One important factor contributing to this further reduction in stiffness may be the misalignment in the direction perpendicular to the load. This would change the force–displacement behaviour of the connection, but modelling the process is outside the scope of this study.

Fig. 10 shows the measured range between unload-reload stiffness intercepts. The value in each case can be thought of as the result of two effects:

1. the misalignment of dowel holes acting to reduce the zero-stiffness range;
2. and the plastic opening of the dowel holes acting to increase it.

In specimens with only one dowel at each end, only the second effect is present, so the zero-stiffness range tends to be greater than the 2 mm due to oversize of the holes in the steel plates. The effect of adding one dowel at each end, to make a two-dowel connection, is in many cases to reduce the zero-stiffness region to below 2 mm. For three or more dowels, however, the zero-stiffness slip increases again, often above 2 mm. One possible explanation for this is that the more dowels are present, the higher the overall load on the connection, and therefore the higher the load that any outlying connector sees. This higher load may cause additional plastic behaviour in the timber around that connection, evening out the load amongst the connections and increasing the zero-stiffness slip.

The hardwood specimens generally have slightly lower zero-stiffness slip than the softwood specimens, suggesting less local plastic deformation in the more dense timber.

The grey lines in Fig. 10 show how the range evolves in each individual specimen. In contrast to the evolution of stiffness, the zero-stiffness range in a specimen with one dowel is not a good indicator of the range for the same specimen with more dowels added. The random offset of dowel holes relative to one another is evident.

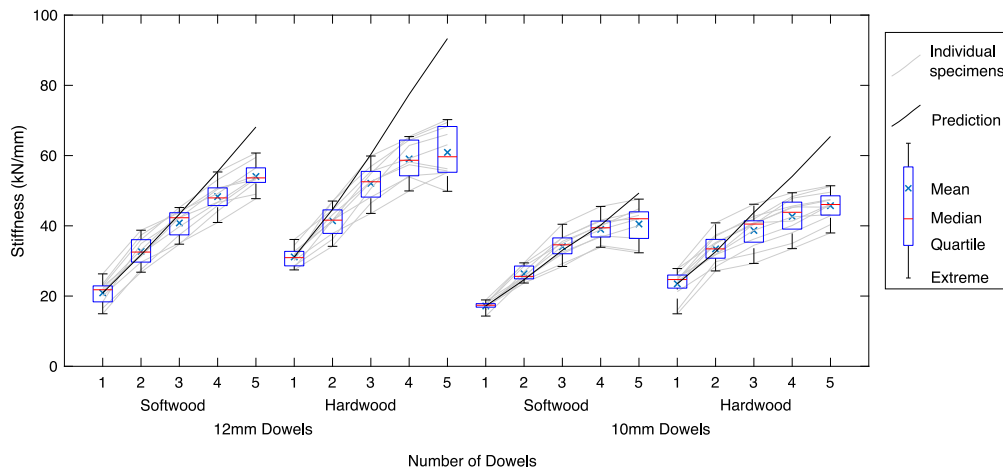


Fig. 9. Unload reload stiffness for connection tests and predictions based on effective numbers of connectors.  $n=10$  for each box (the tension and compression stiffness for each specimen are both included). The “Prediction” is based on the mean predicted stiffness from the Monte-Carlo simulation of dowel offsets.

Table 5  
Stiffness for large specimens.

	Initial stiffness	Elastic stiffness	Effective number of dowels	Zero stiffness region <sup>a</sup>
Softwood	290	423	20.2	1.1 mm
Hardwood	400	520	16.7	1.1 mm

<sup>a</sup>The zero-stiffness region should be compared with half of that in Fig. 10.

### 3.2.2. Large specimens

Fig. 11 shows the lines fitted to the tests on the large specimens. The control system on this actuator prevented the load being held at 10% of the estimated failure load, as was done for the small and medium specimens. Instead, the load was returned to zero before reloading. The initial stiffness and unload-reload stiffness were calculated using the values of force and displacement between 10% and 40% of the estimated failure load, as for the other specimen types. Table 5 show the measured stiffnesses, and the measurement of the zero-stiffness region, measured to the intersection of the elastic stiffness line with zero force.

These results show that the misalignment of the dowels, even in these large specimens, does not remove the zero-stiffness region, and the amount of slip at zero stiffness is commensurate with the effect of the clearance of the dowel from the steel plate. The measured effective number of connectors is given in Table 5, and is substantially less than predicted in Table 4. This suggests that additional processes are restricting the number of dowels contributing to the connection stiffness. In these larger specimens, misalignment along the length of the dowel through the multiple plates may be important.

### 3.3. Consequences for design

This study has shown that the force–displacement response of multi-dowel connections with slotted-in steel plates in timber structures can be characterised, for serviceability conditions, by two effects: a zero-stiffness region and a region which exhibits approximately elastic behaviour. Fig. 12 illustrates this for a softwood connection with three 12 mm dowels.

The zero-stiffness region results from the oversize of the hole in the steel plate and is increased by irreversible deformation at the hole edge under loading, but is reduced by the misalignment of dowel holes in the timber due to manufacturing tolerances.

The approximately elastic behaviour is lower under first loading (the initial stiffness), and increased, and fairly consistent, under subsequent unload-reload cycles. It is not proportional to the number of

dowels, but has group effects which could be represented as an effective number of dowels.

The significance of the zero-stiffness region in design calculations would depend on the nature of the structure, its construction process and the nature of the loading on it. Connections at either ends of bracing elements of multi-storey buildings, for example, might alternate between tension and compression, and see the effect of the zero-stiffness region regularly, whereas bracing elements on bridges might be in either tension or compression for their whole lifespan and see only the initial and unload-reload stiffness.

In connections with screws or self-drilling dowels, the slip due to oversize of the hole in the steel plate would not be applicable, but the slip generated by irreversible deformation would be. The magnitude of the effect in screwed connections requires further research, but back-calculation from the difference between stiffness under initial loading and unload-reload in [3] shows that there is a substantial effect of irreversible deformation for a screw in embedment, up to approximately 0.45 mm for the screws with 12 mm outer thread diameter.

Eurocode 5 [9] predicts the total deflection of the connection as the sum of the oversize of the hole in the steel plate and the initial stiffness, which, based on Fig. 12, will be an underestimate, because the zero-stiffness region is, in practice, reduced to less than the hole clearance. On this basis the value of the initial stiffness between the 10% and 40% loads on first loading does not appear useful. Measured this way, it does not represent the total deformation of the connection, unless the reduction in the zero-stiffness region is also recorded.

## 4. Conclusion

This study has documented the force–displacement behaviour of a range of multi-dowel timber connections, with two dowel diameters, hardwood and softwood specimens and dowel groups ranging from one to five dowels at either end of a symmetrical specimen, as well as large specimens with 35-dowel groups.

It has shown that various non-linear processes substantially affect the force–displacement curve for a connection specimen, in particular:

- the oversize of the holes in the steel plates required for assembly creates a zero-stiffness region;
- plastic deformation in the timber around the hole edge enlarges the hole in the timber and increases this zero-stiffness region;
- the associated densification leads to a higher unload-reload stiffness than initial loading stiffness; and
- misalignment of the dowels in the holes in the steel plate, due to manufacturing tolerances, reduce both the size of the zero-stiffness region and the stiffness of the connection.



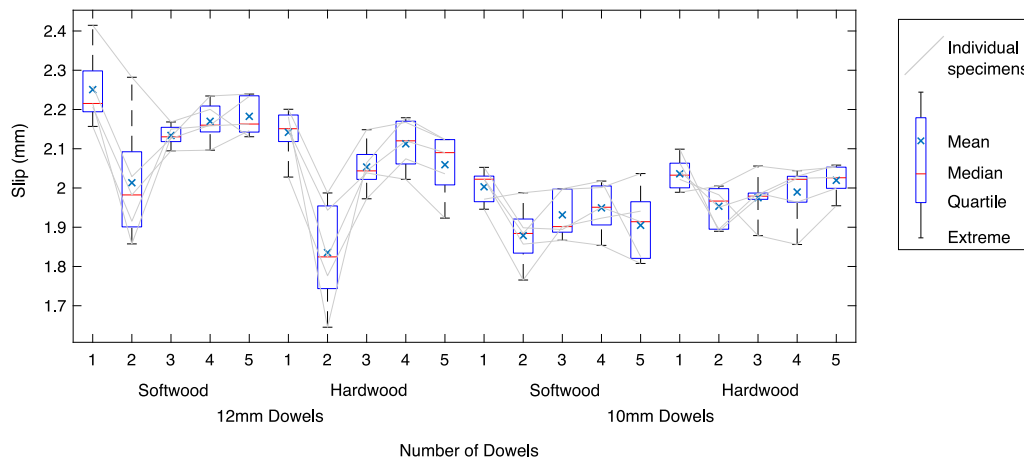


Fig. 10. Zero-stiffness range for connection tests.  $n=5$  for each box.

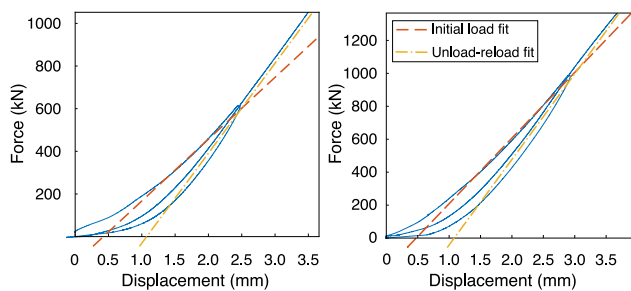


Fig. 11. The measured force–displacement response of the 35-dowel connections in hardwood and softwood, showing fits of the initial loading, and the unload-reload portion of the compressive loading curve.

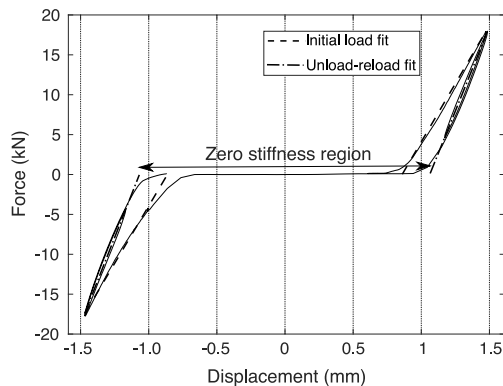


Fig. 12. Measured force–displacement response of a softwood connection with three 12 mm dowels, showing the effect of misalignment on the zero-stiffness region.

For these specimens, the effect of dowel misalignment was of a similar order to the hole opening due to plastic deformation, so that the zero-stiffness region remained approximately 2 mm, due to the 1 mm clearance in the steel plates at each end. This was true for all specimens, including the large 35-dowel connections.

On this basis, two parameters are considered to be important for the design of these connections: the unload-reload stiffness and the zero-stiffness region measured between the zero load intercept of the unload-reload linear fit. With these, a reasonable estimate can be made of the displacement at any serviceability load level in either tension or compression.

### CRediT authorship contribution statement

**Thomas P.S. Reynolds:** Conceptualization (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Writing – original draft. **Will Miranda:** Investigation, Methodology. **Dario Trabucco:** Funding acquisition, Methodology. **Eleni Toumpanaki:** Methodology, Investigation. **Robert M. Foster:** Writing – review & editing. **Michael H. Ramage:** Funding acquisition, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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