A Serviceability Investigation of Dowel-Type Timber Connections Featuring Single Softwood Dowels

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Abstract

Dowel-type connections are common in timber engineering, but current design codes are largely based on empiricism and are oversimplified. This inhibits the optimised use of connections, which is essential for the design of economically efficient timber structures. This study investigates the use of 3D computational modelling to predict the slip modulus (a key measure of stiffness) of single and double shear, dowel-type connections featuring a single softwood dowel. Initial modelling was conducted on parallel- and perpendicular-to-grain connections to establish a suitable mesh size and to validate the model against experimental work. The slip modulus in angled orientations was then investigated, a relationship given no consideration in design codes. The results show that the current design codes greatly overestimate the slip modulus in both single and double shear connections involving timber dowels. In comparison, the models in this study are more than twice as accurate at predicting slip modulus. Furthermore, slip modulus was shown to vary sinusoidally as the grain-to-grain angle changes between the parallel and perpendicular orientations. Differences between model and experimental values can be attributed to uncertainty in the mechanical properties of the timber in the experiments, the assumption of uniform properties for timber in each principal direction in the models, and the inherent variability of timber which affects experimental results.

Keywords—timber connection, slip modulus, Eurocode 5

1. INTRODUCTION

In recent decades structural timber has become an increasingly attractive option as a construction material, having many benefits over its popular competitors, steel and concrete, particularly its sustainability and aesthetic credentials, as well as its impressive strength to weight ratio. Trees are environmentally beneficial; during growth, they promote soil fertility and water retention, protect biodiversity and amenity, and sequester carbon via photosynthesis [1]. It is reported that each kg of wood can sequester up to 1.44kg of CO_2. When used as a construction material timber acts as a carbon store, preventing the release of CO_2 into the atmosphere via decomposition; in addition, every cubic metre of timber used instead of other building materials saves on average 0.8 tonnes of CO_2 [2]. At the end of life, timber can be reused or combusted for biomass energy. The energy required in production only constitutes 15% of the energy potential of the timber and its residues [2]. Additional advantages of using timber in construction include thermal insulation, acoustic absorption, fire and chemical resistance, reduced build time, and reduced construction waste on site.

The application of timber in construction has also increased due to recent innovations, a harmonisation of design codes, and extensive research. Advancements in technology have fostered products such as engineered timber which provide stronger options with few irregularities, e.g. glulam and cross laminated timber [3]. However, solid timber is still used extensively in many applications, offering a cheaper, simpler option which is quick to produce and avoids the degree of processing and manufacturing involved in engineered timber.

Nevertheless, timber remains a challenging material to analyse due to its orthotropic nature where stiffness and strength (and other non-structural properties) differ along three mutually orthogonal axes, a consequence of natural tree growth. Other complications include the growth of imperfections such as knots and resin pockets, and variability in moisture content which further influences strength and stiffness [4].

Practical design of structures in timber is heavily influenced by the nature of the connections between members, and connections are usually weaker than the individual members, hence structural failure is generally caused by the failure of the joints [5]. The design of connections in timber structures is therefore often the dominant factor in governing the size of the members, trumping other factors. Connection design in timber structures is considered to be the crux of the design process due to orthotropy, potential for splitting, significant reduction in cross sectional area in the vicinity of the connection, complex stress transfer mechanisms, and a general lack of understanding in detailing, manufacturing and construction [6]. It is estimated that the design of connections can account for up to 70% of the total effort in designing a timber structure [5], however only 20% of the current European design code, Eurocode 5 (EC5), is spent on connection design [6].

A Nordic study [7] identified that poor connection design was responsible for failure in 23% of timber structures, of which 57% used dowel-type connections. The difficulty in connection design is reflected in the views of experts in the field [6]. In a survey of 412 experienced structural timber engineers, of which 89% had over three years of experience in the industry, the overwhelming consensus was only "average" satisfaction with the design recommendations given in EC5. The survey reported a desire for improvement, particularly in connections, where the practitioners felt the guidance currently required excessive effort to apply and could lead to uneconomic construction. Astonishingly, most felt that Section 8 on connections was unacceptable for day-to-day use, as commercial pressures do not allow much time to complete a design. Similar concerns are evident in a 2007 UK Institution of Structural Engineers publication on EC5 [8] although that statement has been removed from the recently published second edition [9].

One possible solution to the above difficulties is to improve understanding of the behaviour of timber connections via computational modelling, e.g. finite element analysis (FEA). According to [10], modelling not only aids in understanding but also allows questions to be investigated that cannot be approached experimentally. The advancement in computing power has increased the use of FEA in numerous civil engineering applications with the potential to approximate solutions to complex problems with an acceptable degree of accuracy. It avoids the costs of raw materials and expensive testing equipment, and adjustments are easily made, although validation is key. This is the approach used in this study to predict the behaviour of dowel-type timber connections (with single softwood dowels) in the elastic region, an often overlooked but critical part of design, and for cases that are not covered by EC5.

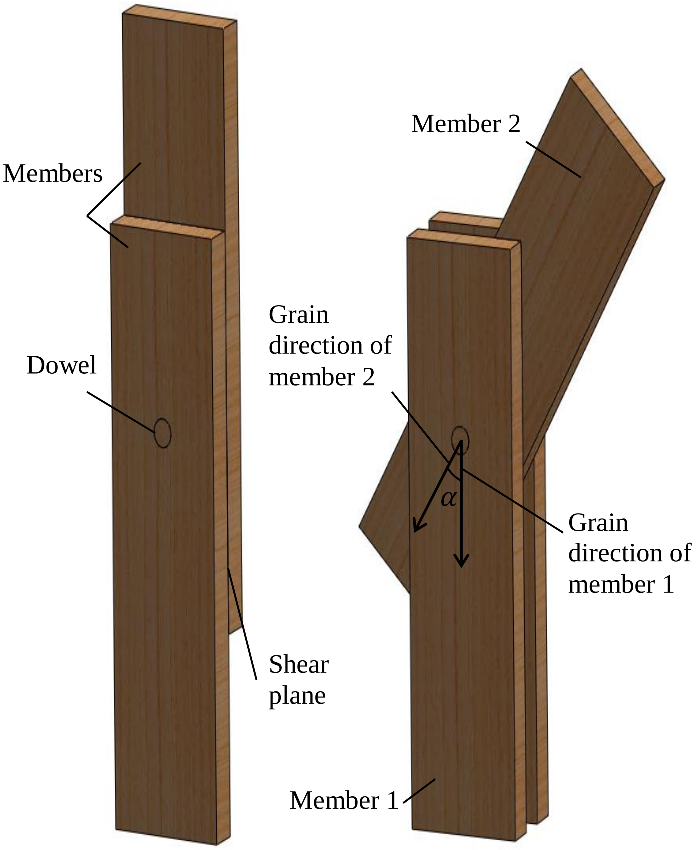
2. ELASTICITY IN DOWEL-TYPE CONNECTIONS

Dowel-type connections (nails, staples, bolts, screws and dowels) are common fastener solutions for timber structures. They are simple to produce and can be used to transmit a range of forces [11]. Dowel-type joints are categorised as shear connections since forces are transferred between members via shear in the dowel but the forces in the members are axial. An example of a single shear joint with the two member grains aligned parallel is shown in Fig. 1(a). A double shear connection is illustrated in Fig. 1(b), in which the grains are oriented at an angle, α, hereon known as the grain-to-grain angle. A value of $\alpha = 0°$ corresponds to a parallel connection, whereas $\alpha = 90°$ represents a perpendicular connection.

There is significant motivation to continue research in timber fasteners. Timber pegs are commonly employed in the restoration of historic timber buildings, where they are preferred to steel, to maintain consistent moisture variation, preserve historic appearance, and uphold the fire and chemical resistance of the structure. Timber dowels are also widely used in the United States in timber frame construction [12].

Most modern structural engineering codes of practice are based on limit state design, which requires that both ultimate limit states (ULS) and serviceability limit states (SLS) are satisfied. The ULS concerns the safety of a structure and its users by limiting the stress that materials experience. The SLS addresses the comfort and practicality of a structure and involves deformations, deflections and vibrations. Previous surveys have shown that in buildings generally, serviceability issues are responsible for most structural defects [13]. The prime serviceability issues are excessive floor and roof deflections, which can cause numerous problems such as jammed doors and windows, slanting furniture, gaps below partitions, dishing of floors, ponding, moisture penetration, damage to services, aesthetic displeasure and a feeling of jeopardy. An example of structural failure due to negligence of the deformation of connections is the Sandö-bridge in the

1930s [6]. Serviceability states are often the decisive factor when verifying the behaviour of existing timber structures or designing new ones [14], i.e. stiffness rather than strength.



a) Single shear, parallel b) Double shear, angled

Figure 1. Dowel-type timber connections

2.1 Connection stiffness standards

Section 8 of EC5 uses the term *slip modulus*, K_{ser}, to estimate the in-service stiffness of all dowel-type connections. Slip modulus is a measure of joint stiffness, i.e. resistance to displacement, hence it has the units N/mm. The determination of slip modulus can be achieved either by using the empirical formula presented in Section 8 [15], or by experiment according to EN26891 [16], in which slip modulus is referred to as k_s.

In EC5, the value of K_{ser} per shear plane per fastener under service load is given by

$$K_{ser} = \rho_m^{1.5} d/23 \tag{1}$$

where ρ_m is the mean density of the timber member in $\mathrm{kg/m^3}$, and d is the dowel diameter in mm. The expression is based on several experiments and derivations carried out by Ehlbeck and Larsen, first published in 1993 [17]. While useful as a quick calculation, it is generally regarded as superficial and oversimplified, and can result in the design of conservative connections [18, 19]. The expression is assumed to be independent of the thickness of the adjoining members as well as the angle between the members in the connection, however it has been shown that these *do* influence joint stiffness [20, 21, 22]. Larger displacements tend to occur in perpendicular connections, as opposed to parallel connections, due to the weaker stiffness of wood perpendicular to the grain [23, 24]. Furthermore, the EC5 Equation is derived from timber connections with metal fasteners, hence the implications of its use in connections with timber dowels remains unanswered.

In the experimental approach, the slip modulus is calculated using a force-displacement curve, in which K_{ser} is assumed approximately equal to the gradient between 10% and 40% of the maximum load. This method usually produces more accurate results, but adds cost in terms of time, labour and resources [25].

The slip modulus is an important design parameter, as it helps quantify structural deformation in any structure involving timber. For example, in steel-to-timber and concrete-to-timber connections the slip modulus is used to calculate deflections by multiplying by a factor of 2.0 [15]. Slip modulus is also used for more specialised fasteners, such as split-ring, shear-plate and toothed-plate connectors although a different expression to Equation (1) is used.

2.4 Angled connections

In many real-world scenarios, connections in structures can be required at any angle between grains, exemplified by the arbitrary value of α in Fig. 1. This is a common occurrence in bracing, truss, and roof structures, as well as moment loaded connections [18,24]. The existing guidance in EC5 only provides a single expression to calculate the slip modulus of dowel-type timber connections for all orientations. This simplification is likely to lead to unrealistic values of slip modulus, resulting in either conservative or optimistic values. A recent proposal for the restructuring of the connections section in EC5 includes recommendations for a new section on connection forces at an angle to the grain [6]. The purpose of the study to be described below is an investigation of connection stiffnesses with respect to grain-to-grain angle which could inform such a proposal.

3. METHODOLOGY

3.1 Model Construction

A series of 36 3D deterministic finite element models were created to investigate the slip modulus of single and double shear connections at grain orientations between 0° and 90°. The commercial FE software Abaqus 2021 was used and the models were validated using experimental data on Scots pine in Frontini *et al*. [26]. Pine wood members and dowels were investigated, with dowel diameters of 10 mm and 20 mm. While it is uncommon to use dowels from the same species as the main members, it is not entirely unknown, and it simplifies the modelling. For example, in most medieval structures in Norway, pine dowels were commonly employed as they were simple to manufacture with hand tools, and the wood was widely available. These hand tools are still used by restoration carpenters to carve softwood dowels, hence the subject remains relevant.

The members and dowels were sized to match those used in the experiments, as shown in Table 1. A 0.2 mm gap between the dowel and hole was modelled as this was determined to be a realistic value [27], and also helped to improve numerical convergence [28].

Table 1. Geometry and Density used in Models

Validation Model	**Dowel Diameter (mm)**	**Timber Density (kg/m^3)**	**Side member dimensions (mm)**	**Centre/side member dimensions (mm)**
SS 10mm 0°	10	463.2	210 x 60 x 30	210 x 60 x 30
SS 10mm 90°	10	448.4	400 x 100 x 30	100 x 60 x 30
DS 10mm 0°	10	494.1	210 x 60 x 30	210 x 60 x 30
DS 10mm 90°	10	438.1	400 x 100 x 30	100 x 60 x 30
SS 20mm 0°	20	463.2	420 x 120 x 30	420 x 120 x 30
SS 20mm 90°	20	448.4	800 x 200 x 30	200 x 120 x 30
DS 20mm 0°	20	494.1	420 x 120 x 30	420 x 120 x 30
DS 20mm 90°	20	438.1	800 x 200 x 30	200 x 120 x 30

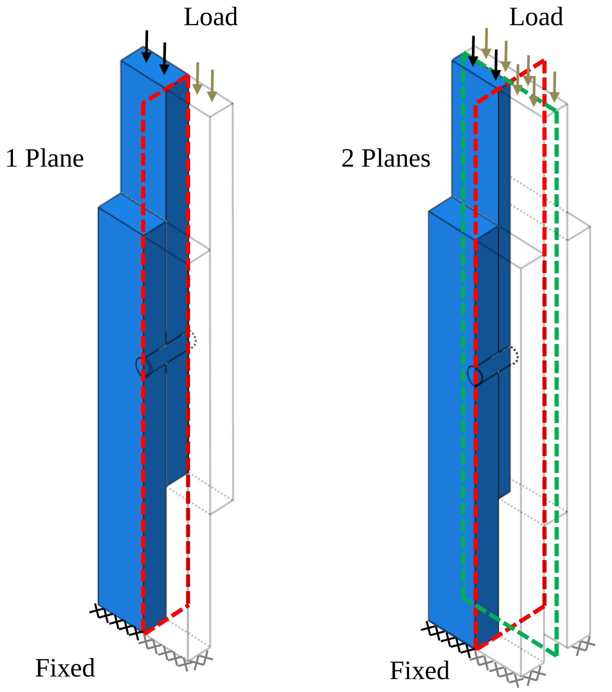
The members and dowels were modelled using hexahedral 8-noded continuum elements with reduced integration and hourglass control (C3D8R). Timber was modelled as an orthotropic material with very little distinction in transverse and radial properties, as verified in [11]. This was implemented by specifying the Young’s moduli, Poisson’s ratios and shear moduli in each principal direction to assemble a set of nine properties as shown in Table 2. The Young’s moduli and shear moduli were taken from the recommended values in the Eurocodes [29]. The values correspond to timber strength class C24 which was the same as used in the experiments. Poisson’s ratios were taken from [30, 31], which provide an average value, calculated from softwood species with a similar density to Scots pine. In the validation stage the mean density from the specific series was used for both model and EC5 prediction, as shown in Table 1.

Table 2. Elastic properties of timber members and dowels used in models

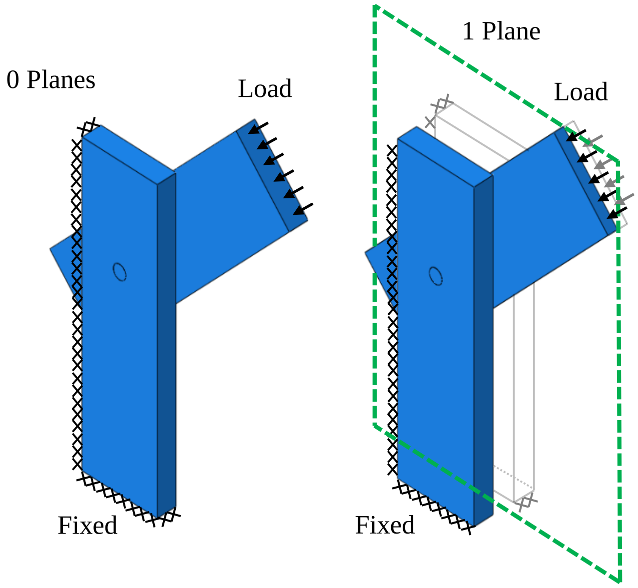
(Axes are along the grain, L, radial, R and transverse, T)

Property (units)	Value
E_L (GPa)	11.0
E_R (GPa)	0.37
E_T (GPa)	0.37
v_{LR}	0.346
v_{LT}	0.349
v_{RT}	0.402
G_{LR} (GPa)	0.69
G_{LT} (GPa)	0.69
G_{RT} (GPa)	0.69

A static implicit analysis was used, with displacement control over a series of increments. Measurements of nodal displacement and reaction forces were recorded at each increment. The maximum size of each increment was limited to provide an adequate number of data points (a minimum of five) from which slip modulus could be obtained. Increment size was specified as a fraction of the total period of the applied displacement step. Although increment size varied between models, a fraction of 0.025 was typical. Geometric non-linearity was applied to account for the evolving geometry of the connection. Accommodating such a non-linearity is common in these types of FE model [4].



a) Single shear, $\alpha = 0^\circ$ b) Double shear, $\alpha = 0^\circ$



c) Single shear, $0^\circ < \alpha < 90^\circ$ d) Double shear, $0^\circ < \alpha < 90^\circ$

Figure 2. Planes of symmetry applied to models

The contact between parts was modelled using standard surface-to-surface contact (using the Coulomb friction model) via a penalty method with a friction coefficient, $\mu = 0.1$. Contact modelling in the literature varies greatly, with friction coefficients ranging from 0.0 to 0.7 [32, 33]. Sjödin et. al. [34] investigated the effect of friction on single dowel joints, reporting slip modulus to be almost consistent between tests with rough surfaced dowels ($\mu = 0.4$). However, for smooth surfaced dowels ($\mu = 0.1$), the elastic response varied considerably between tests. In [26] the response was seen to vary significantly, with standard deviations in stiffness as high as 0.64 N/mm, hence a value of $\mu = 0.1$ was used in the models. Larger values of friction coefficient were also trialled, but the accuracy of the models decreased, supporting the use of 0.1. In the interaction between dowel and member, the dowel was assigned the master surface (due to having a finer mesh), whilst the member was the slave.

Symmetry was used when geometry, loading and results were symmetric about a plane to increase analysis efficiency. The symmetry used in each of the 36 models can be summarised in four cases as shown in Fig. 2. For single shear connections with the grains parallel, one plane of symmetry is applied, allowing only $1/2$ of the connection to be modelled. The parallel double shear connection exhibits 2 planes of symmetry allowing $1/4$ of the joint to be modelled. For single shear with orientations between 0° and 90° the loading and geometry do not permit any planes of symmetry hence the full connection was modelled. Lastly, for double shear joints at orientations between 0° and 90° only one plane of symmetry is permitted hence $1/2$ of the connection was modelled. It should be noted that perpendicular connections follow the same symmetry conditions as the parallel case.

Three types of boundary condition were applied to the models. A fixed boundary condition was applied to nodes at the base of the lower member. In cases where $0° < \alpha < 90°$, this boundary condition was extended to nodes in the side of the lower member to eliminate deformation due to bending of the member. This is shown in Figs 2(c) and 2(d). Secondly, non-zero nodal displacements were imposed on the top surface of the upper member to simulate compression of the connection under load. The magnitude of displacement was taken to be $0.2d$, where d is the diameter of the dowel in mm, as this was found to be sufficient to produce the necessary axial force to extract slip modulus from the resulting force-displacement curve. These upper nodes were assigned zero lateral displacement to avoid convergence errors. Lastly, the Abaqus symmetrical boundary condition (essentially a roller boundary condition) was applied to nodes located on planes of symmetry, restraining displacement in the direction normal to the plane.

3.2 Evaluation of K_{ser}

Once a simulation was complete, the model slip modulus, K_{model}, was extracted from the output history. Nodal reaction forces at the fixed supports were summed. They were then plotted against the displacement of a node at the top of the upper member, producing a force-displacement curve. It should be noted that this is not the same method as that used to obtain the slip curves in the experiments, and it includes additional elastic deformation from the members. However, it simplifies the data extraction from the models and provides more accurate results.

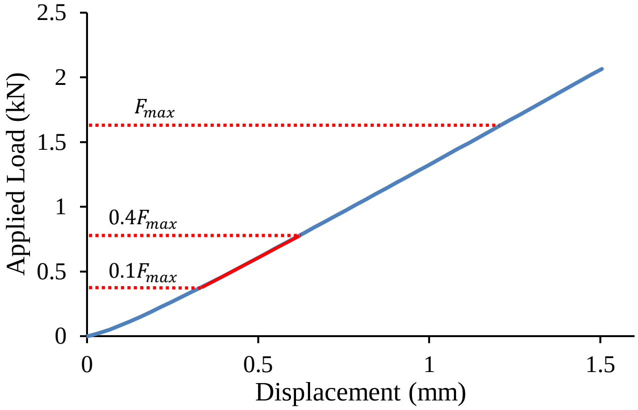


Figure 3. Example force-displacement curve obtained from models

From the graph, linear regression was performed on points between $0.1F_{max}$ and $0.4F_{max}$ to obtain K_{model}. Here, F_{max} is the maximum load the connection could withstand, derived from the experiments. Figure 3 illustrates a typical force-displacement graph obtained from the FE model and the method of calculating K_{model}. The plot is initially non-linear, followed by a near linear region, minimally affected by evolving geometry and contact conditions. It should be noted that the initial small gradient of the curve is a consequence of the dowel-hole gap that is included in the models. This simulates the typical real-world behaviour of dowel-type connections in which a low initial gradient is observed due to the closure of the dowel-hole gap.

Due to the applied symmetry, in some cases only a fraction of the complete connection was modelled. This influences the corresponding value of K_{ser}, analogous to a set of springs in parallel. For example, in the case of one plane of symmetry and one shear plane, the obtained model slip modulus was doubled, as without the plane of symmetry, twice the load would need to be applied to obtain the same displacement. The relationship is presented in Equation (2), where K_{ser} is slip modulus per shear plane in kN/mm, K_{model} is the model slip modulus in kN/mm, n_{sym} is the number of planes of symmetry and n_{sp} is number of shear planes.

$$K_{ser} = K_{model} \times 2^{(n_{sym} - n_{sp} + 1)} . \tag{2}$$

The equation provides an adjustment to K_{model} depending on the number of symmetry and shear planes, allowing different connection geometries to be easily compared and presents them in the same format as Equation (1).

3.3 Sensitivity study

A preliminary sensitivity study was carried out on the parallel double shear case with a 10 mm dowel to determine the optimum mesh size to use in the models. This case was chosen as it was only necessary to model $1/4$ of the connection, therefore reducing analysis time. The model was created and initially simulated using a very coarse mesh. Results were obtained for K_{ser}, the number of elements, and the simulation time.

The mesh was then refined in regions of large stress gradients, i.e. the circumference of the dowel and the immediate timber surrounding the dowel. The process of mesh refinement mesh is shown in Fig. 4, in which slip modulus first increases rapidly as the number of elements increases, before slowing and eventually a plateau is observed. The plateau value of approximately 2.45 kN/mm was taken as the desired slip modulus,

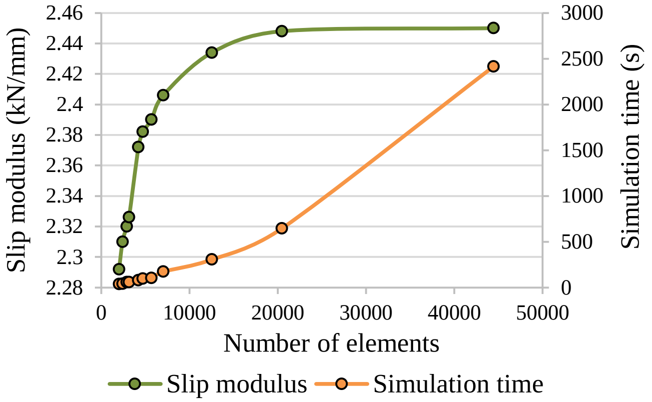


Figure 4. Slip modulus and simulation time in response to number of elements in model

i.e. the exact solution. In contrast, simulation time steadily increases with the number of elements before increasing more quickly after approximately 18,000 elements.

The error in slip modulus for any mesh size iteration was defined as the difference between the desired slip modulus and the slip modulus for that iteration. The percentage error in slip modulus was plotted against simulation time as shown in Fig. 5.

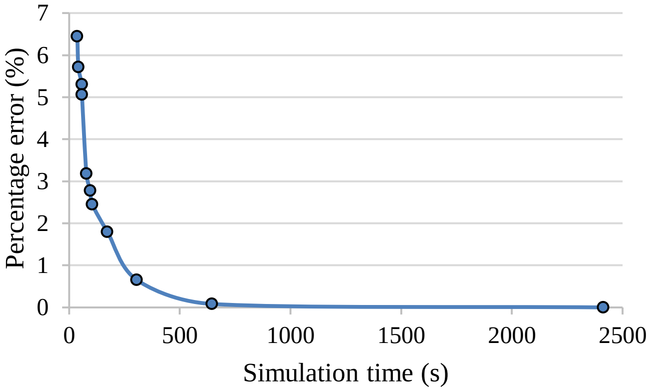


Figure 5. Computational cost of reducing percentage error in K_{ser}

The study shows that percentage error initially decreases rapidly as simulation time is increased. Notably, a 5% error can be reached with a relatively coarse mesh in as little as 60 seconds. However, once a simulation time of around 100 seconds is reached the percentage error decreases more gradually and after 300 seconds any attempt to further decrease the error is met with steep computational costs. A sudden increase in computational time occurs in the transition from 3% error to 2% error, in which CPU time increases by 76% in comparison to the decrease in error from 4% to 3%, which only adds an additional 21% of simulation time. It is clearly inefficient to seek a 2% error. Therefore, an error of 3% was deemed acceptable, considering the savings in computational time and the comparatively large disparity between model and experimental slip modulus. From Fig. 5, the acceptable error of 3% corresponds to a simulation time of approximately 85 seconds, which, in turn requires approximately 4500 elements. Hence it was decided that around 4500 elements should be used for this case as a compromise between accuracy and computational effort. For the other models, a similar mesh density was used so that an appropriate number of elements were used to account for different planes of symmetry across models.

3.4 Model Validation

The models were validated based on 44 experiments carried out by Frontini *et al.* [26]. Successful validation was based on obtaining comparable results to the experimental data for the parallel and perpendicular connections, in both single and double shear, and with dowel diameters of 10 mm and 20 mm. Eight models were built to represent each of the variations using the mesh density determined from the sensitivity study. The value of K_{ser} obtained from each model was compared against both the experimental value and the result obtained from the Eurocode 5 recommendation, i.e. Equation (1). The results of model validation are displayed in Fig. 6. The standard deviations of the experimental results are indicated by error bars.

All three methods yield similar trends, with parallel and perpendicular cases producing slightly different values for the 10 mm dowel followed by a large increase in slip modulus for the 20 mm dowel. Out of the three variables (the number of shear planes, orientation and dowel size), dowel diameter is most influential on K_{ser}. In terms of orientation, the perpendicular connections tend to be slightly lower stiffness than their parallel equivalents. Whilst the model approximation can be seen to overestimate K_{ser}, the EC5 approximation greatly exceeds the experimental value by a minimum factor of 3.0 across all cases. This factor peaks at 6.9 for the perpendicular, single shear case with a 20 mm dowel. This is a considerable overprediction, meaning current guidance appears greatly to underestimate the in-service deformation of dowel-type connections involving timber dowels. In comparison, the model values of K_{ser} lie much closer to the experimental values, exceeding by a mean factor of 2.1 (compared to 5.0 for EC5). The model most accurately predicts the parallel single shear case using a 20 mm dowel, exceeding the experimental value by a factor of 1.43.

The difference between model and experiment can be partly explained by the variability of the timber in the experiments. Timber was modelled with uniform properties in each principal direction. This assumption is not true for real timber as local weaknesses and irregularities exist, meaning lower values of stiffness are likely to be observed, particularly if these localities lie within the dowel. Differences can also be explained by the uncertainty in the mechanical properties of the timber in the experiments. The Young's Moduli, Shear Moduli and Poisson's ratios were not provided in the experimental data; hence values could only be assumed for the models. The timber used in the experiments was sourced from a local Norwegian sawmill which graded the timber as C24. Such grading is often done visually without mechanical testing. For the purpose of investigating timber connections, this inevitably introduces a high degree of uncertainty.

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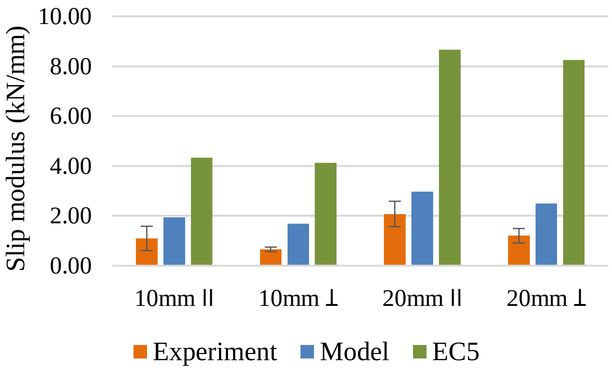
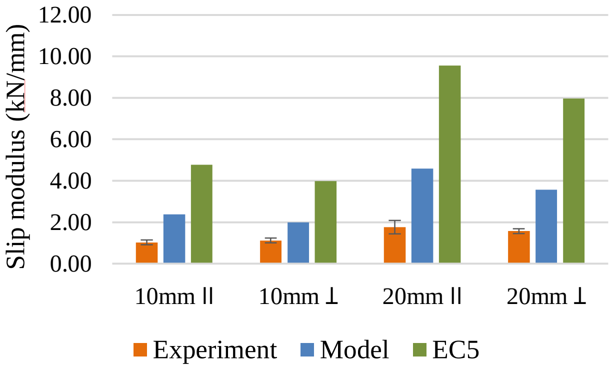
The large difference between the experimental and EC5 values is due to the suitability of the EC5 Equation to the type of investigated connection. Although the EC5 Equation remains the current guidance for all dowel-type connections, it was derived from timber connections using metal fasteners. For connections with metal dowels, the timber embedment properties may govern the connection stiffness, however, timber dowels have a much lower embedment stiffness compared to steel dowels. When shear loads are transferred between members, embedment deformation in the dowel will dictate K_{ser} since the dowel is loaded perpendicular to the grain. Therefore this study showcases a scenario for which the EC5 Equation is not strictly suitable and provides some magnitude for the inaccuracy obtained.

However, as the models show, a technique encompassing a more comprehensive set of parameters can be used to achieve a better prediction of real-world timber connections, in which economic design and resource use are crucial for business and environmental benefits.

It is problematic to make conclusions about individual parameters from the results of validation. As well as the three investigated factors, the experiments used four different densities of timber. Whilst this was accounted for in the models, it is unclear what effect this had. Furthermore, in reality the material is highly anisotropic and can contain many irregularities. The impact of this intrinsic property of timber can be seen in the experimental data in the change from parallel to perpendicular orientations in the double shear 10 mm dowel, where slip modulus *increases*. This is unexpected as slip modulus should decrease to coincide with the lower stiffness in the cross-grain direction, a trend shown in all other cases. Furthermore, slip modulus



a) Single shear



b) Double shear

Figure 6. Validation of parallel and perpendicular models with 10 mm and 20 mm dowels

increases despite a decrease in timber density of 12.8%, another contradiction since Equation (1) states that K_{ser} should increase with timber density. This is a clear demonstration of the inherent variability of timber.

3.5 Angled Orientations

After validation against experimental data on parallel and perpendicular connections, the effect of α on K_{ser} was investigated in a series of 28 models. The member widths were set to $8d$, increased from $6d$, where d is dowel diameter in mm, to meet the EC5 minimum edge distance requirement due to the different orientation of the load. As there were no experiments carried out on angled connections, the mean of the densities in Table 1 was used. This is shown in Table 3, along with the geometry of the connections. The investigation was conducted by varying the angle of the upper member in 15° increments from 0° to 90°. An example of a model with $\alpha = 30°$ is shown in Fig. 7, along with the applied boundary conditions and mesh density determined from the sensitivity study.

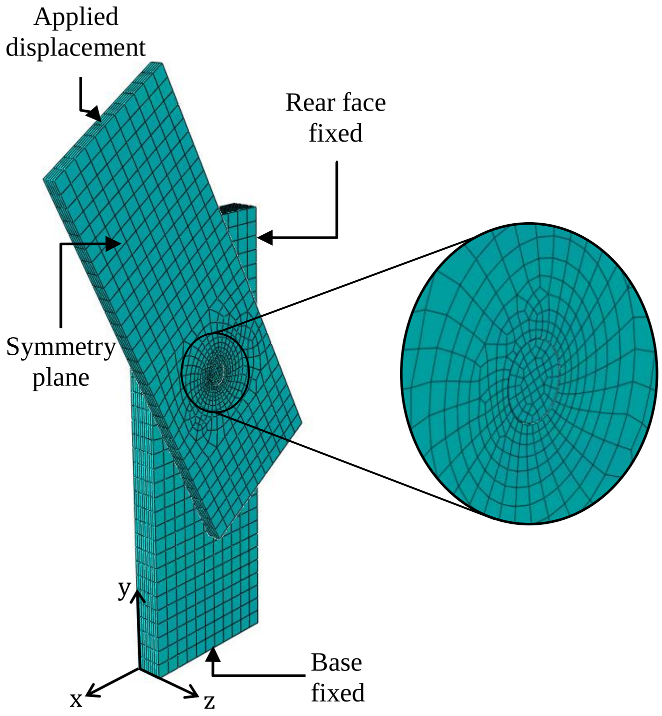


Figure 7. Double shear connection model, 20 mm dowel, $\alpha = 30°$, boundary conditions and mesh size

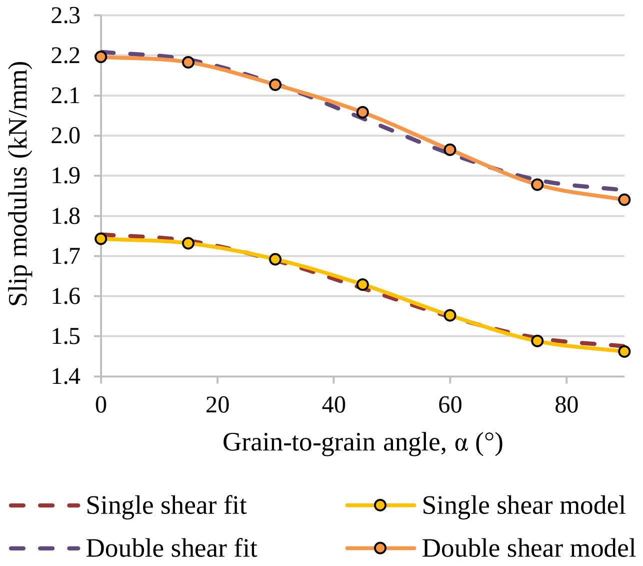
Table 3. Geometry and Density in Angled Models

Connection Type	**Dowel Diameter (mm)**	**Timber Density $(\mathrm{kg/m^3})$**	**Side member dimensions (mm)**	**Centre/side member dimensions (mm)**
SS 10mm	10	460	210 x 80 x 30	210 x 80 x 30
DS 10mm	10	460	210 x 80 x 30	210 x 80 x 30
SS 20mm	20	460	420 x 160 x 30	420 x 160 x 30
DS 20mm	20	460	420 x 160 x 30	420 x 160 x 30

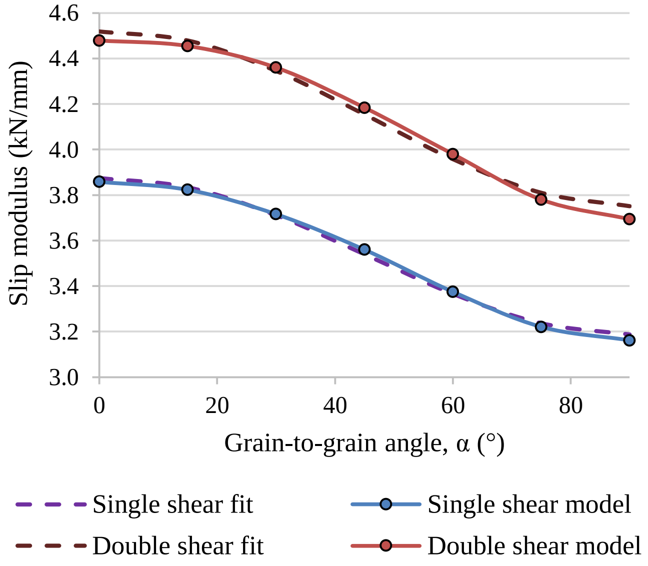
From the results of each simulation a nodal displacement was taken from the face of applied displacement, as in Section 5.2. As a value of F_{max} was not available for the angled orientations, linear interpolation was performed on the parallel and perpendicular cases from the experiments. In the fixed member the nodal reaction forces in each direction (in this case x and y) were used to obtain the total reaction force in the line of applied displacement. The reaction force magnitude was then plotted against nodal displacement to produce a force-displacement curve and hence slip modulus values obtained.

4. RESULTS AND DISCUSSION

The results of the 28 simulations are summarised in Fig. 8, with separate plots for the two dowel sizes. Each data point represents the result of one computational analysis. It should be noted that values outside the investigated range of geometries remains a topic of interest. All curves follow the same trend with a maximum value of K_{ser} at $\alpha = 0°$ and a minimum value at $\alpha = 90°$. This is not surprising as a higher slip modulus is expected in the parallel orientation due to the greater stiffness of timber in the grain direction. All



a) 10 mm Dowel



b) 20 mm Dowel

Figure 8. Variation of slip modulus with grain-to-grain angle

trends show a similar reduction in K_{ser} when oriented perpendicular, dropping to approximately 83% of their peak value.

This orientation-based relationship was easily observed in the parallel models. Even at low load levels, the dowel sustained the majority of the deformation, with the members experiencing relatively small deformations in comparison, concentrated in the contact area. The dowels were loaded transversely to their fibres, resulting in displacements of up to 8.7 times larger than those in the members, which were loaded longitudinally. This demonstrates a benefit of using hardwood or steel dowels, as greater stiffness properties in the dowel are critical for reducing deformation of the entire connection.

It is also interesting to note that slip modulus increases with Poisson's ratio and shear modulus. Simulations on the 20 mm double shear case revealed approximately a 2% increase in K_{ser} when the Poisson's ratio in each direction was increased by 10%, and a 2.5% increase when shear modulus was increased by 10% in each direction. This can be attributed to the increased contact pressure and frictional shear stress that occur between contact pairs, requiring a greater force to cause the same level of connection deformation. These observations demonstrate that slip modulus is influenced by all ten mechanical properties used in the investigation.

For values in between the maximum and minimum the curves follow a sinusoidal trend. Little change is observed close to the peak and trough whereas the greatest rate of change in K_{ser} is observed at around $\alpha = 45°$. Sinusoidal trendlines have been fitted to the curves which are discussed later.

The type of connection has a significant impact on K_{ser}. The double shear connections yield a greater value of slip modulus per shear plane by a mean factor of 1.22 across all models. This is surprising, since the number of shear planes is accounted for in the evaluation of K_{ser}. However, one major difference is the application of symmetry in the models. The double shear connection features symmetry offset from the x-y plane. Upon application of this boundary condition in Abaqus, no movement in the z-direction is permitted which maintains the strict alignment of the connection.

In the single shear connection, there is no equivalent boundary condition, freeing the upper member to move in such a plane. This was observed in the simulations, in which the upper member rotated slightly due to the uneven application of the force. This perhaps provides a second reason to prefer double shear connections, in addition to providing a second shear plane which means K_{ser} can be multiplied by 2.0 to obtain the total slip modulus of both shear planes. The experiments confirm this trend with double shear exceeding single shear by a mean factor of 1.21.

However, due to the different timber densities used (and ever-present orthotropy and irregularities), there is significant variance in the comparison between single and double shear experiments. In some tests, single shear even outperformed the double shear equivalent in terms of K_{ser}, highlighting a major benefit of modelling since the influence of other factors can be negated.

Following an approach similar to [35], the sinusoidal trendlines were fitted to the model data as shown in Fig. 9 using curves that can be represented by

$$K_{ser} = \left(\frac{K_{ser,0}-K_{ser,90}}{2}\right)\cos(2\alpha) + 1.01\left(\frac{K_{ser,0}+K_{ser,90}}{2}\right) \tag{3}$$

where $K_{ser}, K_{ser,0}$ & $K_{ser,90}$ are in kN/mm, and $K_{ser,0}$ and $K_{ser,90}$ refer to the slip modulus for the parallel and perpendicular models respectively. These vary depending on the type of connection and are given in Table 4.

Table 4. Parameters used to fit each model data series

Connection type	$K_{ser,0}$ (kN/mm)	$K_{ser,90}$ (kN/mm)
SS 10 mm	1.74	1.46
DS 10 mm	2.20	1.84
SS 20 mm	3.86	3.16
DS 20 mm	4.48	3.69

The sinusoidal fit provides a good approximation of the relationship between slip modulus and grain-to-grain angle. The fit is least accurate at $\alpha = 0°$ and $\alpha = 90°$, where it overestimates K_{ser} by at most 1.6%, indicating still a close fit. However, the fit is unable to perfectly describe the data suggesting that the $K_{ser} - \alpha$ relationship is not perfectly sinusoidal.

The results of this study, both the validation and investigation of α, have considerable real-world implications. The EC5 expression considered in this investigation is used for all dowel-type fasteners, comprising the majority of simple mechanical structural fasteners. Therefore, an overprediction of slip modulus could lead to unexpected actual excessive structural deformations between members joined via these fastener types which could cause a range of serviceability issues, leaving a structure unable to satisfy the requirements it was designed to fulfil.

EC5 also requires slip modulus to determine the bending stiffness of beams and deflections of columns, indicating the clear link between the investigated design parameter and the movement of structural members. Lastly, a closer inspection of EC5 reveals that the slip modulus used for ultimate limit state calculations, K_u, is derived directly from K_{ser} [15], hence an incorrect prediction of the in-service slip modulus could lead to a false estimate of structural behaviour in the upper elastic region and plastic region.

5. CONCLUSIONS

This investigation has assessed the suitability of using three-dimensional computational modelling to predict the serviceability behaviour of dowel-type single and double shear connections featuring timber dowels. It has also explored the relationship between the slip modulus and the grain-to-grain angle between connected members. The aim of the investigation was to increase the understanding of real-world structural connections involving a material that is difficult to analyse but is becoming more popular due to its environmental credentials. From the results of this study, the following conclusions can be drawn:

i. The current EC5 equation to determine slip modulus appears to greatly overestimate the stiffness of single and double shear connections for all orientations when softwood timber dowels are specified. This is because the EC5 equation is derived from tests on timber connections with metal dowels and the findings of this study highlight the implications of its use when softwood dowels are specified. Otherwise, this could have severe implications in design, in cases where a structure may experience excessive deflections due a fundamental error in the design code.

ii. The 3D models in this study provide a far more accurate method to explore slip modulus variation, saving on time, expensive testing equipment and raw materials. The models prove that the elastic behaviour in both single and double shear connections can be predicted to a much greater degree of accuracy than previously obtainable via the EC5 method.

iii. For the connection types investigated in this study, perpendicular connections are on average 83% as stiff as parallel connections provided all other factors remain constant. Therefore, the timber members are best aligned with their grains parallel if low deformation is desired. Of course, this cannot always be the case. For angles between the parallel and perpendicular orientations, as is common in real-world situations, the connection slip modulus follows a sinusoidal trend.

iv. Computational modelling can be used to explore complex questions and investigate single variables without interference from other factors. This is especially advantageous for timber, which is notorious for influencing experimental results with high levels of variance due to its orthotropy and irregularities.

v. As the model uses elastic constants based on timber strength class, and Poisson's ratios averaged from a range of softwoods, the models can be used to determine K_{ser} for other softwoods with similar densities and member widths. However, this should be applied with caution, as explained in the limitations of the investigation below.

5.1 Reflections

Due to the inherent variability of timber the models cannot perfectly predict the behaviour of the connections and the physical properties of natural timber cannot simply be reduced to nine engineering constants. These are only approximations and some properties, such as Poisson's ratios, are difficult to measure [10]. The experimental data used only five or six repetitions, and for such an irregular material, inaccuracies are likely to be present. Hence, when validating a model against such experiments, it is uncertain whether the true solution is being reached. However, considering the time constraint placed on the investigation, an acceptable level of accuracy has been achieved and the models are more than twice as accurate at predicting slip modulus compared to the EC5 method.

As linear elastic material properties were assumed, the models can only simulate the connection behaviour while in service, i.e. before yielding occurs. It cannot be used to predict the complex brittle behaviour of the timber after yielding.

In terms of individual variables, only a single dowel was modelled. Therefore, the models cannot be used for multi-dowel configurations or slotted-in steel plates. The models have only been validated for members with a width of 30 mm, and a dowel diameter between 10 mm and 20 mm. Values outside of this range remain a topic of interest.

The investigated relationship between grain-to-grain angle and slip modulus is unprecedented in experimental work for angles between 0° and 90°. It would be worthwhile to see if the sinusoidal relationship uncovered in this study holds in mechanical testing.

To further develop the computational approach, several possibilities exist. It would be beneficial to investigate whether the models are suitable for predicting the slip modulus in connections containing hardwood and steel dowels, and to compare the model approximation against the Eurocode recommendation. Although timber pegs are increasing in popularity, steel dowels remain the most common at present. This is not surprising as the dowel experienced the largest deformations so opting for a dowel with greater stiffness should greatly decrease global joint deformation. It is expected that the design codes should provide a more accurate prediction of slip modulus in steel dowels. Alternative models, such as the beam-on-foundation model presented in [20], may provide more accurate results and would be worthwhile to investigate.

The experimental work used in this investigation also included tests on “straight traditional pegs”, a dowel with octagonal cross-section rather than circular, and found that these exhibited a greater stiffness due to the tight fit of the peg [26]. Hence, it would be useful to assess the suitability of computational modelling to predict the behaviour of timber dowels with different cross sections.

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