<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Wood Material Science & Engineering*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Bader, T., Schweigler, M., Hochreiner, G., Serrano, E., Enquist, B. et al. (2015)
Dowel deformations in multi-dowel LVL-connections under moment loading.
Wood Material Science & Engineering, 10(3): 216-231
<http://dx.doi.org/10.1080/17480272.2015.1070372>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-46194>

Dowel deformations in multi-dowel LVL-connections under moment loading

[Thomas K. BADER^{1,3}](#), [Michael SCHWEIGLER¹](#), [Georg HOCHREINER¹](#), [Erik SERRANO²](#), [Bertil ENQUIST³](#),
[Michael DORN³](#)

¹ Institute for Mechanics of Materials and Structures, Vienna University of Technology, Vienna, Austria.

² Division of Structural Mechanics, Lund University, Sweden.

³ Department of Building Technology, Linnaeus University, Växjö, Sweden.

Wood Material Science & Engineering, 10(3):216-231, 2015.

<http://dx.doi.org/10.1080/17480272.2015.1070372>

Available under the conditions of *Green open access* as the post-print version of the accepted article. See also

<http://www.sherpa.ac.uk/romeo/search.php?issn=1748-0272>

Dowel deformations in multi-dowel LVL-connections under moment loading

Thomas K. Bader^{1,3*}, Michael Schweigler¹, Georg Hochreiner¹, Erik Serrano², Bertil Enquist³, Michael Dorn³

¹Institute for Mechanics of Materials and Structures, Vienna University of Technology, Karlsplatz 13, A-1040 Vienna, Austria; thomas.bader@tuwien.ac.at; T: +43 1 58801 20228

²Division of Structural Mechanics, Lund University, Sweden

³Department of Building Technology, Linnaeus University Växjö, Sweden

**Corresponding author. E-Mail address: thomas.bader@tuwien.ac.at; Tel.: +43 1 58801 20228*

Abstract

The aim of the experimental study presented herein is the assessment and quantification of the behavior of individual dowels in multi-dowel connections loaded by a bending moment. For this purpose, double-shear, steel-to-timber connections with nine steel dowels arranged in different patterns and with different dowel diameters were tested in 4-point bending. In order to achieve a ductile behavior with up to 7° relative rotation, the connections were partly reinforced with self-tapping screws. The reinforcement did not influence the global load-deformation behavior, neither for dowel diameters of 12 mm nor for 20 mm, as long as cracking was not decisive. The deformation of the individual dowels was studied by means of a non-contact deformation measurement system. Thus, the crushing deformation, i.e. the deformation at the steel plate, and the bending deformation of the dowels could be quantified. In case of 12 mm dowels, the bending deformation was larger than the crushing deformation, while it was smaller in case of 20 mm dowels. Moreover, dowels loaded parallel to the grain showed larger bending deformations than dowels loaded perpendicular to the grain. This indicates that the loading of the individual dowels in the connection differs, depending on their location.

Keywords: Dowel Connection; Bending Moment; Load Distribution; Timber; Ductility; Reinforcement

Introduction

Dowel connections are often favored in the design of timber structures, since, if properly designed, they exhibit a highly ductile behavior (see e.g. Blaß and Schädle 2011). The reason for that lies in the ductile embedment behavior of steel dowels in timber, which is a prerequisite for plastic deformations of steel dowels. Due to the anisotropic mechanical behavior of timber, the behavior of dowel connections depends on the orientation of the loading with respect to the grain direction. Under typical load situations, different load orientations can be present in multi-dowel connections, which, consequently, lead to an unequal distribution of the load to the individual dowels.

The aim of the experimental study presented herein is the assessment and quantification of the behavior of individual dowels in multi-dowel connections loaded by a bending moment. For this purpose, double-shear steel-to-timber connections with steel dowels are tested. Due to global bending, different load directions on the single dowels are present. In addition to the global loading and the deformations of the timber beams, the deformations of the individual dowels are monitored during testing. The steel-to-timber connections enforce equal deformations of all dowels at the steel plate. However, the bending deformation of the steel dowels is expected to depend on the specific load-to-grain direction. These properties, namely the bending deformation and the corresponding deformation direction of the dowels, will be studied herein by means of contact-free deformation measurement methods. Thus, differences in the behavior of single dowels with respect to the load direction can be visualized and quantified. The influence of different dowel arrangements and dowel diameters will be investigated. The connections are designed to avoid brittle failure modes and to allow for large single dowel deformations. This is achieved through large dowel spacing and reinforcement by means of self-tapping screws. The influence of the reinforcement by self-tapping screws on the global and local behavior of the dowel connections, will be assessed by comparing unreinforced and reinforced connections. Since several growth irregularities of wood, such as knots, may affect the local behavior of dowels, laminated veneer lumber (LVL) is used herein. In addition to multi-dowel connections, single-dowel connections as well as the embedment behavior of LVL and steel dowel properties under bending have been assessed for the same material and for the same dimensions as used herein.

Investigations on steel-to-timber dowel connections have been a research topic drawing a lot of attention within the timber engineering community for many years. Thus, a large number of research papers have been published, starting with the early work of Johansen (1949). Other important work in more recent years includes e.g. Madsen (2000), Blass and Bejtka (2008) and Jorissen (1998), or Quenneville and Mohammad (2000). Most of the research has related to the behavior of either single-dowel joints (including embedment tests) or multi-dowel joints in tension. In the latter case, the aim has often been to predict the effect of having several dowels in a row and/or to determine proper distances between dowels or end- and edge distances in order to avoid brittle failure modes due to splitting of the wood. The corresponding characteristics of dowel connections have been studied for loads parallel (see e.g. Dorn et al. 2013) and perpendicular (see e.g. Schoenmakers and Jorissen 2011; Jensen et al. 2012) to the grain.

Relating to the main aim of this paper, namely the detailed studying of the deformation behavior of individual dowels in connections loaded in bending, available literature is scarce. Recently, Bruehl et al. (2011) studied the rotational stiffness of dowel connections in order to be able to describe the ductile behavior of such connections in timber structures. Bouchaïr et al. (2007) investigated the influence of the orthotropic characteristics of wood on the behavior of individual dowels in moment-resisting joints by a combination of experimental and numerical methods with the aim to enhance the modeling of the load distribution among dowels. As regards ductility in timber structures, this is mainly achieved through dowel-type connections. Different strategies to avoid brittle failure modes and to ensure a ductile behavior of dowel-type connections, and consequently of timber structures, were e.g. presented by Blass and Schädle (2011).

Non-contact deformation measurement methods have been applied in previous research of dowel connections, see e.g. Sjödin et al. (2006, 2008). In these studies, deformations on the surface of the wood were recorded in order to illustrate and quantify the loading of the wooden matrix by the dowels. Moreover, the development of failure in wood can be followed by this method. As a novel issue of the work presented herein, the monitoring of dowel deformations in addition to the surface deformations of the wood will be assessed. Thus, this work additionally aims to evaluate the possibilities of non-contact deformation measurement systems in the analysis of dowel connections.

Materials and Methods

Steel dowel connections

Laminated veneer lumber (LVL) produced from spruce wood with parallel oriented veneers only (Kerto-S®, Metsä Wood, Finland) with a density of 0.495 g/cm³ was used in this study. The thickness of the timber beams used in the tests was 114 mm, which resulted from a combination of two 51 mm thick LVL beams and a 12 mm Oriented Strand Board (OSB) in between (Fig. 1a). Multi-dowel connections were manufactured in one end of the LVL beams. For this purpose, a steel plate with a thickness of 10 mm was used in the connection area where the OSB plate was left out and the steel plate could be inserted into the 12 mm gap. In the transverse direction, steel dowels with diameters of 12 or 20 mm were inserted into pre-drilled holes to establish the connection.

The behavior of multi-dowel connections was investigated experimentally by subjecting dowel groups consisting of nine dowels to a pure bending moment. Table 1 gives an overview of the different connections and their characteristics together with the number of test specimens. Different dowel arrangements, namely in a *squared* or *circular* manner, were tested (Fig. 1b and c). Two different dowel diameters, 12 and 20 mm, were chosen. The spacing between the steel dowels as well as the edge distance were 120 mm and identical for both dowel diameters. This resulted in a height of the LVL beam of 480 mm. The distance between the dowels and the end grain of the beam was 180 mm. In case of 12 mm dowels, the spacing and edge and end distances were considerably larger than the minimum spacing given in the current design standards, while for the 20 mm dowels the spacing was only slightly larger than the minimum requirements. Consequently, a pronounced ductile behavior of the connections could be expected at least for connections with 12 mm dowels. In order to increase the ductility even more and to allow for large dowel deformations in the connections, some of the connections were reinforced (see Table 1). For this purpose, self-tapping screws (SFS WR-T-9x500®, SFS Intec, Switzerland) with a diameter of 9 mm and a length of 500 mm were inserted into pre-drilled holes on both sides and in between the steel dowel connections (Fig. 1b and c). All timber elements were conditioned at 20°C and 65% relative humidity before testing.

Rods with circular cross section and diameter of 12 and 20 mm made from the steel quality S235 were used as raw material for steel dowels. Subsequently, these rods were heat-treated at 750 °C in a low oxygen environment (to avoid oxides on the surface) with a controlled cooling down process. Through this procedure, uniform material properties of the steel dowels could be expected. Material properties were measured in tensile tests. Test specimens had diameters of 10 or 12 mm, which were shaped from 12 mm and 20 mm rods, respectively, using a lathe. In addition, 3-point bending tests were performed on 12 and 20 mm dowels, in order to characterize material's deformation capacity at large strains in bending. The load was applied by means of a stiff loading device made of steel. Support plates were separated by rollers, in order to allow them to slide in relation to each other during the test. The lower support plate was in turn supported by a pinned support, allowing both horizontal and vertical reactions to be transferred to ground. Free span between the pinned supports was 180 mm. Displacement controlled loading was used in all cases. The test set-up made it straightforward to evaluate the bending moment at mid-span by: a) assuming that the support plates are separated by perfect rollers, i.e. without any friction and b) by measuring the mid-point displacement and the rotation of the support plates.

4-point bending test of connections

The behavior of the connections under pure bending was studied by means of a 4-point bending test set-up, as illustrated in Fig. 2. First of all, only one LVL-to-steel connection was tested with this set-up, since only one half of the test set-up consisted of the LVL beam, while the other half was made of a steel beam. Thus, failure is guaranteed to take place in the timber part. Secondly, since a non-contact displacement measurement system with fixed positioned cameras was used during testing, it was important to minimize vertical displacement in the area of interest. Therefore, the loads were applied at the ends of the beams and the beam was supported at the inner triple points. In order to have symmetric loading and deformations of the set-up, the steel beam was designed to have a bending stiffness similar to that of the timber beam. The pistons at the end of the beams were driven from the same hydraulic pump, thus approximately identical forces were applied. The cross-section of the steel beam consisted of two welded U-sections with the connection plate in the center. The length of the steel and the LVL beams were 2.4 m and 3.1 m, respectively, with a total span of 5.1 m between the loading points. The dowel connection was placed in the center of the span where a loading in pure bending was expected. The displacement rate was around 6 mm/min up to failure, or up to a maximum displacement at the loading points of 100 mm, respectively.

Load and deformation measurements

During testing, loads and displacements were measured continuously. The loads were measured with load cells with a capacity of 50 kN at each loading point. Displacements were measured with potentiometers at different locations as indicated in Figure 2. The maximum piston range was 100 mm, which was also the maximum range for the displacement potentiometers. The loads were further used to calculate the bending moment in the center of the dowel connection by means of equilibrium conditions of the statically determined beam structure.

On one side of the joint, a non-contact displacement measurement system (*Aramis*®, Gesellschaft für Optische Messtechnik mbH, Germany) was used. This made it possible to measure the complete displacement field of the area of the connection. Since also the steel plate was partly covered by the full-field deformation measurement system, the rotation of the timber part relative to the steel plate, i.e. the relative rotation of the connection, was measured. The assumption of the center of rotation of the steel plate to be located at the geometrical center of the connection, i.e. the center dowel, allows defining the relative deformation of the individual dowels at the steel plate with respect to their initial position in the LVL. In the following, these deformations will be denominated as the *crushing deformations*, which are illustrated in Fig. 3. The direction of the crushing deformation is in the opposite direction of the relative rotation of the timber beam, which is illustrated by an arrow in Fig. 3a

Furthermore, the protruding visible ends of the dowels were equipped with markers, thus allowing for a 3D-trace of the dowel ends using point-tracking software (*Pontos*®, Gesellschaft für Optische Messtechnik mbH, Germany). Additional markers were placed on the steel plate. Therefore, the relative deformation of the ends of the dowels with respect to the steel plate, i.e. the *bending deformation* of the dowels, could be calculated (Fig. 3b), as well as the corresponding direction of the bending deformation. The dowels protruded approximately 10-15 mm over the LVL beam. Herein, the *bending deformation* of the steel dowels at the surface of the LVL is presented. The bending deformation was back-calculated assuming a linear shape of the bending of the dowels and a length of the dowels of 52 mm as the distance from the steel plate to the surface of the LVL. The sketched deformation shape of the steel dowel in Fig. 3 is naturally a simplification of the real bending behavior of the steel dowel.

Production and assembly of connections

The LVL/OSB beams were manufactured at a commercial carpentry shop, gluing together two LVL halves (each 51 mm thick) with a 12 mm OSB panel in the middle. The OSB was left out in the joint area, so that a 12 mm gap was formed in which the 10 mm steel plate could be fitted. The steel plates were drilled CNC-controlled with the desired hole patterns, using drills of diameter 12 and 20 mm, respectively. The steel plates were then also used as templates for drilling the holes in the LVL beams. The drilling of the holes in the LVL was done a few weeks before the testing, and thus a certain amount of drying/moistening of the LVL occurred. This led to minor problems at the assembly of the joints and as a result some force had to be applied in order to fit the dowels. In conclusion, the dowels fitted tightly and consequently no slip was expected.

Results and Discussion

Global behavior of multi-dowel connections

The global behavior of the connection exposed to a bending moment can be described by its slip behavior, i.e. by the relative rotation of the beams due to the compliant behavior of the joint, which in turn is due to the dowels' interaction with the LVL and the bending of the dowels. Being clearly a function of the relative rotation, the load level is plotted over the relative rotation in the center of the connection (Fig. 4 and Fig. 5). Although precautions were taken to prevent this, an unbalanced stiffness of the steel and LVL beams could cause an additional shear force in the connection. In all tests, the shear force (as calculated from equilibrium conditions) was smaller than 2 kN, whereby in eight of twelve connections, the shear force was less than 0.5 kN. Thus, single steel dowels could have been loaded by up to 0.2 kN in shear. Since this is very small compared to the loading due to the bending moment as well as compared to the strength of the single-dowels, the global shear force is considered to be negligible.

As intended by the test set-up, a pronounced ductile behavior of the dowel joints was observed for both dowel diameters. As regards the 12 mm dowel groups (Fig. 4), the relative rotation between the LVL and the steel beam was up to about 7°. Except for connections of *Type A*, no global failure of the connections with 12 mm dowels was observed up to this relative rotation. In all cases, the loading was limited by

100 mm deformation at the outer supports of the 4-point bending test configuration. As expected, the squared pattern of dowels yielded higher bending moments than the circular pattern of the same dowels. This is due to the larger distance of the dowels from the center of the joint to the corners of the square dowel pattern as compared to the distance of the dowels in the circular pattern joints. In general, the reinforced and unreinforced dowel joints behaved similarly. Only one joint of *Type C* showed a slightly higher moment than the other joints with this pattern. This might be a consequence of variations in the dowel properties or local material properties of the LVL. The reinforced connections behaved similar to the unreinforced connections. Thus, the moment-rotation behavior of the connections was not affected by the reinforcement. The rotational stiffness of the connection is calculated as the derivative of the moment-rotation curve with respect to the relative rotation (Fig. 4). The rotational stiffness is obviously higher for the squared pattern compared to the circular pattern, for the same reasons as outlined above for the moment capacity. Rotational stiffness starts to decrease already at very small deformations. This might indicate that plastic deformations in the steel dowels or in the wood already occur at the corresponding deformation levels.

Similar to the connections with 12 mm dowels, only minor variations between the same types of connections were observed for connections with 20 mm dowels (Fig. 5). Also, higher bending moments in the connections with a squared pattern than in connections with a circular pattern were observed. Compared to the connections with 12 mm dowels, loads were considerably higher. Consequently, the maximum bending moment was twice the maximum moment acting on the 12 mm dowel joints. Here, the effect of the reinforcement becomes obvious when comparing reinforced and unreinforced connections of series F, where first load drops due to splitting are observed at about 1.5° relative rotation. Consistent with the 12 mm dowel connections, the reinforcement does not have any effect on the behavior of the connection up to that point. The rotational stiffness of the connections with 20 mm dowels is considerably higher and a more extended range of “elastic” behavior of these connections becomes obvious, when compared to the 12 mm dowel connections. This can be explained by the 20 mm dowels being stiffer and having a higher yield moment than the 12 mm dowels.

The bending moment results in the different dowels being loaded at different load-to-grain directions. However, since all the connections are symmetric, symmetric deformations of the connection are expected with the center of rotation located in the geometrical center of the connection, i.e. at the center dowel. The corresponding expected initial load-to-grain directions are 0, 45, and 90° . The magnitude of the bending deformation in relation to the crushing deformation of each dowel will allow studying the failure mode of the single dowels. In the following, the corresponding characteristics of the dowel deformations in the multi-dowel connections tested will be discussed.

Steel dowel material properties

Tensile tests of the heat-treated steel dowels revealed very uniform yield strength of about 300 MPa for both dowel diameters, as well as considerable straining up to 20% nominal strain without any considerable softening. The corresponding material behavior is illustrated in Fig. 6, by means of a stress-strain relationship. The bending moment-rotation behavior of the heat-treated material was investigated in a 3-point bending test setup (see Fig. 6). Compared to tensile tests, a considerable hardening effect became obvious in the bending tests. Yield moments of 135 Nm and 550 Nm at bending angles of 10.9° and 9.6° for dowels with a diameter of 12 and 20 mm, respectively, were measured (see Fig. 6).

Dowel deformations of 12 mm dowels in squared pattern (Series A and C)

Fig. 7 illustrates the behavior of the 12 mm dowels arranged in a squared pattern. For illustration purposes, the results of the test *CD12_R_01* are chosen. Fig. 7a shows the crushing deformations (blue) and the bending deformations (red) of the individual dowels over the entire test. The steel plate serves as a rigid reference. The bending deformation of the center dowel was close to zero, which confirms the assumption that the center dowel is the center of rotation of the dowel group. Thus, the shear force in the dowel group is negligible. The same behavior was observed for the other specimens of the same type (*Series A* and *C*). Also, the bending deformations of the dowels (red in Fig. 7a) follow closely the deformation directions prescribed at the steel plate.

Clearly, the bending deformations and the crushing deformations of the individual dowels plotted over the relative rotation of the connection separate the dowels into two groups: the *corner dowels* and the dowels that are horizontally or vertically aligned with the center dowel (hereafter termed *inner dowels*), see Fig. 7. This is expected since all dowels within a group have the same distance from the center of the

connection. Consequently, only small differences within these groups are encountered. For the four corner dowels, not only the distance but also the deformation-to-grain angle is equal, namely about 45° (Fig. 7c). Their bending deformations were up to 20 mm and the crushing deformations were up to 18 mm. On the contrary, the inner dowels are loaded either parallel or perpendicular to the grain. Plotting the bending deformations of the dowels over the relative rotation of the connection reveals slightly higher bending deformations for the dowels loaded parallel to the grain than for the ones loaded perpendicular to the grain (see Fig. 7b), while the crushing deformations are equal (see Fig. 7d). The bending deformations of the inner dowels were up to 15 mm with corresponding crushing deformations of up to 13 mm. Related to the global moment, the behavior of the individual dowels is consistent with the global moment-rotation relationship, i.e. a stiff initial behavior is quickly followed by a continuous decrease. This indicates plastic deformations taking place already at small relative deformations (starting at a bending deformation of less than 0.3 mm). Bending deformations of all dowels are larger than the crushing deformations (cf. Fig. 3b,d), i.e. the compression deformation on the outer surface of the specimens is in the opposite direction compared to the loading at the steel plate.

The directions of the bending and the crushing deformations of the dowels are presented in Fig. 7c. Dashed blue lines represent the deformation-to-grain angles for the crushing deformation and the red lines represent the corresponding angles for the bending deformation. The directions of the crushing deformations start, as expected from the type of loading, at angles close to 0, 45 and 90° with respect to the grain. Since the deformation directions follow a circular path with the center at the geometric center of the connection, the directions of the crushing deformations start to deviate from the above mentioned values with increasing relative rotation. The magnitude of these deviations is equal to the relative rotation of the connection. Deviations from these directions over the loading are visible for the bending deformation. Interestingly, this is particularly the case in the beginning of the loading, while the directions of the bending deformation approach the directions of the crushing deformation at later loading stages. Obviously, the calculation of the bending deformation directions is somewhat numerically sensitive if the deformations are small. Furthermore, this might be due to the fitting of the dowels to the bore holes and the steel plate, which would take effect at initial load stages. At later stages, dowels are enforced to follow the deformation of the steel plate, which results in a circular deformation path. Still, small deviations of the expected deformation directions are present at later loading stages.

Dowel deformations of 12 mm dowels in circular pattern (Series B and D)

For illustration purposes, results of the test *BD12_U_02* are illustrated in Fig. 8. The bending deformation of the center dowel was close to zero which confirms the assumption that the center dowel is the center of rotation of the dowel group and that the shear force is negligible. The same behavior was observed for all specimens of this type (*Series B* and *D*). Also, the bending deformations of the dowels (red in Fig. 8a) closely follow the deformation directions prescribed at the steel plate.

Plotting the bending deformations and the crushing deformations for the individual dowels over the relative rotation of the connection highlights small deviations between the single dowels (Fig. 8b). Since all dowels do have the same distance to the center of rotation, as compared to the squared arrangement, similar deformations of all dowels are expected. Similar to the dowels in a squared pattern, the load-to-grain directions are about 0, 45 and 90° . The crushing deformations are equal for all dowels, but differences are observed for the corresponding bending deformations (Fig. 8b). Indeed, the largest bending deformations are again observed for the dowels loaded parallel to the grain, while dowels loaded perpendicular to the grain show smallest bending deformations. The crushing deformations were up to 15 mm with corresponding bending deformations of up to 19 mm for dowels loaded parallel and 17 mm for dowels loaded perpendicular to the grain, respectively. Thus, the bending deformations of the dowels are larger than their crushing deformations. Related to the global moment, the behavior of the individual dowels is consistent with the global moment-rotation relationship, i.e. a continuous decrease of the stiffness is encountered after a short stiff initial behavior. This indicates plastic deformations taking place already at small relative deformations (starting at a bending deformation of less than 0.3mm).

The directions of the bending and the crushing deformations of the dowels are presented in Fig. 8c. The directions of the crushing deformations start, as expected from this type of loading, at angles close to 0, 45 and 90° with respect to the grain. Consistent with series A and C, the directions of the crushing deformations start to deviate with increasing relative rotation. Small deviations from the expected bending deformation directions over the loading are visible in Fig. 8c. This is particularly the case in the beginning of the loading, while the deformation directions approach the expected deformation directions at later loading stages. Possible reasons for these deviations have been discussed above.

Dowel deformations of 20 mm dowels in squared pattern (Series E)

For illustration purposes, results of the test *ED20_R_02* are presented in Fig. 9. A slightly larger center dowel deformation compared to the 12 mm dowel tests is observed (Fig. 9b). Since the deformation direction is perpendicular to the grain, the reason for this is most likely a minor shear force. Nevertheless, the center dowel is again assumed to be the center of rotation of the connection. Therefore, minor differences between the direction of the crushing and the bending deformations of the dowels are visible in Fig. 9a. In the second replication of this type of connection, smaller deformations of the center dowel were observed. This might be an explanation for the slightly higher strength of the latter connection (cf. Fig. 5). However, the data on the single-dowel behavior is consistent for the two specimens.

Clearly, the bending deformations and the crushing deformations of the individual dowels plotted over the relative rotation of the connection separate again the dowels into two groups: inner dowels and corner dowels (Fig. 9b). This is expected and consistent with the results of the connections with 12 mm dowels and only small differences within the groups are encountered. For the corner dowels, not only the distance but also the initial deformation-to-grain angles are equal, namely 45° . The corresponding bending deformations were up to 15 mm and the crushing deformations up to 19 mm. On the contrary, the inner dowels are initially either loaded parallel or perpendicular to the grain. Plotting the bending deformations of the dowels over the relative rotation reveals slightly higher bending deformations of the dowels loaded parallel to the grain than for the ones loaded perpendicular to the grain (see Fig. 9b), while the crushing deformations are equal. The bending deformations of the inner dowels were up to 11 mm and 9 mm for dowels loaded parallel and perpendicular to the grain, respectively, with corresponding crushing deformations of up to 13 mm. Thus, the bending deformations of dowels with a diameter of 20 mm are smaller than the crushing deformations (cf. Fig. 9b,d), i.e. the compression deformation at the outer surface of the specimens is in the same direction as the loading at the steel plate (which is different compared to 12 mm dowels). The individual behavior of the single dowels is consistent with the global moment-rotation relationship, i.e. a continuous decrease of the stiffness is encountered after a short stiff initial behavior. This indicates plastic deformations already taking place at small dowel deformations (starting at bending deformations of less than 0.5 mm). This is considerably later than for joints with 12 mm dowels.

The directions of the bending and the crushing deformations of the dowels are presented in Fig. 9c. Deviations of the bending deformation directions from the directions of the crushing deformation are observed. In the beginning, these deviations are more pronounced than in case of 12 mm dowels, which might be explained by the stiffer dowels in Series E requiring a higher force to enforce the load direction.

Dowel deformations of 20 mm dowels in circular pattern (Series F)

For illustration purposes, results of the test *FD20_R_01* are presented in Fig. 10. Since the center dowel bending deformation is comparably small, it seems to be reasonable to assume a loading of the connection in pure bending and the center of rotation being located at the center dowel.

Plotting the bending- and the crushing deformations of the individual dowels over the relative rotation of the connection highlights small deviations between the dowels (Fig. 10b). Since all dowels have the same distance to the center of rotation, as compared to the squared arrangement, similar deformations of all dowels are expected. Similar to the dowels in a squared pattern, the expected load-to-grain directions are 0° , 45° and 90° . The crushing deformations are equal for all the dowels (Fig. 10c), but differences are observed for the corresponding bending deformations (Fig. 10b). The largest bending deformations are again observed for the dowels loaded parallel to the grain, while dowels loaded perpendicular to the grain show smallest bending deformations. In the tests, the crushing deformations were up to 15 mm. The corresponding bending deformations were up to 13 mm and 10 mm for dowels loaded parallel and perpendicular to the grain, respectively. The behavior of the individual dowels is consistent with the global moment-rotation relationship, i.e. a continuous decrease of the stiffness is encountered after a short stiff initial behavior. This indicates plastic deformations taking place already at small dowel deformations (starting at a bending deformation of less than 0.5 mm).

The directions of the bending and the crushing deformations of the dowels are presented in Fig. 10c. The deformation directions are consistent with the other tests. The relative rotation of the connection was up to 6° . Up to about 1.5° relative rotation of the connection, the behavior of the unreinforced joint *FD12_U_01* was similar to the behavior of the reinforced joint as regards both the global behavior and the behavior of the individual dowels, after that the behavior differs due to continuous cracking

Deformations of single dowels

As discussed before, the dowel *bending deformation* in relation to the *crushing deformation* is different for different dowel diameters as well as for different load-to-grain directions. For comparison, all data collected for the 12 connections tested is illustrated in Fig. 11. For both dowel diameters, the bending deformations of the dowels loaded parallel to the grain (Fig. 11a) are larger than the bending deformations perpendicular to the grain (Fig. 11c), while the bending deformations of dowels loaded at 45° are in between these limits (Fig. 11b). Obviously, the different embedment behavior of LVL at different grain angles leads to different loads acting onto the dowels, which, in turn, results in different bending deformations. Different load distribution along the dowels might contribute to these observations. The behavior of the dowels is a reason of the development of one plastic hinge at the slotted-in steel plate.

The relationship between crushing and bending deformation is surprisingly linear. However, dowels with a diameter of 20 mm show initially (up to 0.5 to 1.5 mm crushing deformation) a lower slope of the curve with a subsequent transition to a second linear path (Fig. 11). This might indicate the transition from elastic to plastic bending of the dowels. Also here, the weaker behavior of LVL perpendicular to the grain results in a more extended elastic behavior as compared to the behavior parallel to the grain. Consequently, unloading of the connection would be expected to reduce the bending deformation of the dowels by this small initial elastic deformation of 0.5 to 1.5 mm. A corresponding characteristic of the 12 mm dowels is not visible in Fig. 11. Thus, there is hardly any elastic deformation, and consequently hardly any elastic loading of these dowels. These observations are consistent with the relationship between the relative rotation and the crushing deformation discussed before, since from the beginning they are linear in case of 12 mm dowels (Figs. 7 and 8), while a linear relationship up to crushing deformations of about 1 mm becomes obvious in case of 20 mm dowels (Figs. 9 and 10).

Deformations on the surface of the LVL beam

As discussed before, the deformations observed at the surface of the LVL will be different for different dowel diameters. In case of 12 mm dowels, compression deformations will show up on the opposite side of the actually loaded side at the steel plate, while it will be on the same side for 20 mm dowels. This is exemplified in Fig. 12 for a comparison of 12 and 20 mm dowels in a circular pattern where results of test *BD12_U_02* and test *FD20_R_01* are shown. Particularly in the strains perpendicular to the grain (ϵ_y) at dowels loaded perpendicular to the grain, the different compression sides (blue areas in right images in Fig. 12) are clearly visible.

Since surface deformations were recorded over the entire load history, also onset of failure of the connections could be followed on the surface of the LVL beams. For the type of multi-dowel connections under bending investigated herein, several effects contribute to failure. First of all, splitting of the LVL can be caused by tensile stresses perpendicular to the grain due to the wedging action of a dowel loaded parallel to the grain. Secondly, there are loads acting perpendicular to the grain, i.e. certain dowels are loaded or do have a load-component in this direction. As a third possibility, high shear stresses along the outer edges of the dowel groups are encountered. There are regions where a combination of shear stresses and stresses perpendicular to the grain will cause failure of the connection. This is clearly visible on the surface of the LVL and is illustrated in Fig. 13 for test *A_D12_U02*, an unreinforced specimen with square dowel pattern. In Fig. 13, areas of high strains perpendicular to the grain (ϵ_y) and high shear strain (ϵ_{xy}) indicate cracking. Splitting and cracking of wood in case of unreinforced connections led to a redistribution of the forces, which was well visible in the strains parallel to the grain, i.e. the effective height of the LVL beam was reduced.

Inspection of test samples

After testing, all connections were visually inspected in order to identify the failure mode of the dowels. This is only indirectly accessible through the deformation data discussed before. Clearly, the failure mode of all dowels was one plastic hinge that developed at the slotted-in steel plate. The angle of the bending deformation on the outside of the dowel was measured and documented (see Figure 14). The values are slightly higher than the corresponding angles calculated from the deformation of the dowel heads during loading. In the latter case, the local bending deformation of the dowel close to the steel plate is not accounted for, neither is elastic bending. The deformation of the LVL under a 12 mm dowel is characteristic for the failure mode with one plastic hinge in the dowel. Highly compressed wood is visible

in the vicinity of the steel plate, while there is contact between the dowel and the wood at the outer side of the side member (see Fig. 14c). In addition, the placing of the reinforcement was checked in order to ensure that the reinforcement did not affect the local behavior of individual dowels. All the reinforcements were well in place, having a distance of at least 15 mm from the dowels in the deformed state for the circular pattern and even more for the rectangular pattern.

Conclusions

A very ductile behavior of the investigated connections (as intended) with relative rotations up to 7° was achieved. Connections with 12 mm dowels did not fail up to that point, but the loading was limited by the maximum deformation at the load introduction. The arrangement of dowels in a squared pattern yielded a higher moment capacity of the connection as compared to a circular pattern. Also, connections with 20 mm dowels showed a stiffer global behavior and higher moment capacity compared to connections with 12 mm dowels. It could be demonstrated that the reinforcement did not influence the global load-deformation behavior for any of the dowel diameters unless fracture occurred. This became particularly obvious from the test on connections with 12 mm dowels, where no effect was observed up to very large dowel deformations.

Results of single dowel deformations show that 20 mm dowels had smaller bending deformations due to their higher elastic stiffness and the higher yield moment compared to the 12 mm dowels. In case of 12 mm dowels, the bending deformation was larger than the crushing deformation, while it was smaller in case of 20 mm dowels. Consequently, compressive deformations on the borehole surface of the LVL were on opposite sides. Moreover, dowels loaded parallel to the grain showed larger bending deformations than dowels loaded perpendicular to the grain. This indicates that the loading of the individual dowels in the connections differs, depending on their location relative to the center of rotation of the connection. Hardly any elastic behavior was present in the test with 12 mm dowels, while an elastic initial response of the 20 mm dowels could be observed in the relation between the crushing and the bending deformation. Due to homogenous material properties of LVL, a low variation in the single dowel bending deformations was observed.

The use of a non-contact deformation measurement system has proven suitable for the assessment and quantification of single dowel deformations. Thus, the developed testing procedure could be applied to assess deformations of dowels in other types of wood based materials, as well deformations of other dowel-type connectors.

As a perspective of this work, the relationship between global loading of the connection and forces acting on the individual dowels can be established by putting the results presented herein in relation to tests on single dowel connections.

Acknowledgements

The authors gratefully acknowledge the financial support of the Austrian Research Promotion Agency and the wood industry partnership Building with Wood within CEI-Bois for funding the research work within project MechWood 2. This work forms part of that project. The MechWood 2 research partners are thanked for their cooperation and collaboration in this project.

References

- [1] Blaß, H.J., Bejtka, I. Numerische Berechnung der Tragfähigkeit und der Steifigkeit von querzugverstärkten Verbindungen mit stiftförmigen Verbindungsmitteln. Universitätsverlag Karlsruhe, Karlsruhe, 2008 (in German).
- [2] Blaß, H. J., Schädle, P. (2011) Ductility aspects of reinforced and non-reinforced timber joints, *Engineering Structures* 33(11):3018-3026.
- [3] Bouchair, A., Racher, P. Bocquet, J.F. (2007) Analysis of dowelled timber to timber moment-resisting joints, *Materials and Structures* 40:1127–1141.
- [4] Brühl, F., Kuhlmann, U., Jorissen, A. (2011) Consideration of plasticity within the design of timber structures due to connection ductility. *Engineering Structures* 33(11):3007-3017.

- [5] Dorn, M., de Borst, K., Eberhardsteiner, J. (2013) Experiments on dowel type connections. *Engineering Structures* 47:67-80.
- [6] Jensen, J.L., Quenneville, P., Girhammar, U.A., Källsner, B. (2012) Splitting of timber beams loaded perpendicular to grain by connections – Combined effect of edge and end distance. *Construction and Building Materials* 35:289–293.
- [7] Johansen, K.W. (1949) Theory of Timber Connections, *International Association for Bridge and Structural Engineering* (ABSE) Pub. 9, 249-262.
- [8] Jorissen, A. Double Shear Timber Connections with Dowel Type Fasteners. PhD thesis, TU Delft. Delft University Press, Delft, The Netherlands, ISBN: 90-407-1783-4, 1998.
- [9] Madsen, B. Behaviour of timber connections. Timber Engineering, Ltd., 2000.
- [10] Quenneville, J.H.P., and Mohammad, M. (2000) On the failure modes and strength of steel-wood-steel bolted timber connections loaded parallel-to-grain. *Canadian Journal of Civil Engineering*, 27:761-773.
- [11] Sjödin, J., Serrano, E., Enquist, B. (2006) Contact-free measurements and numerical analyses of the strain distribution in the joint area of steel-to-timber dowel joints. *Holz als Roh- und Werkstoff* 64: 497–506, Springer Verlag.
- [12] Sjödin, J., Serrano, E., Enquist, B. (2008) An Experimental and Numerical Study of the Effect of Friction in Single Dowel Joints. *Holz als Roh- und Werkstoff* 66: 363–372, Springer Verlag.
- [13] Schoenmakers, J.C.M. (Dennis), Jorissen, A.J.M. (2011) Failure mechanisms of dowel-type fastener connections perpendicular to grain. *Engineering Structures* 33(11), 3054-3063.

Tables

Table 1: Overview of different connections experimentally investigated in bending tests.

Joint type	Pattern	Dowel diameter	U=Unreinforced R=Reinforced	Number of replications
A	Squared	12 mm	U	2
B	Circular	12 mm	U	2
C	Squared	12 mm	R	2
D	Circular	12 mm	R	2
E	Squared	20 mm	R	2
F1	Circular	20 mm	U	1
F2	Circular	20 mm	R	1

Figures

Figure 1: (a) Cross-section through the beam and different patterns as used in the dowel connections: (b) *squared* and (c) *circular* pattern. Dimensions are given in mm.

Figure 2: 4-point bending test setup for connection tests. Dimensions are given in mm.

Figure 3: (a) Relative rotation of the multi-dowel connection at the slotted-in steel plate and (b) illustration of crushing and bending deformation of the steel dowels.

Figure 4: Bending moment vs. relative rotation of the connections with 12 mm dowels; solid lines represent unreinforced and dashed lines reinforced dowel connections (cf. Table 1), dotted lines represent rotational stiffness.

Figure 5: Bending moment vs. relative rotation of the connections with 20 mm dowels; solid lines represent unreinforced and dashed lines reinforced dowel connections (cf. Table 1), dotted lines represent rotational stiffness.

Figure 6: (a) Tensile tests on 10 and 12 mm steel dowels (manufactured from 12 and 20 mm rods): Nominal stress versus engineering strain; (b) 3-point bending tests on 12 and 20 mm steel dowels: bending moment versus total rotation at the supports.

Figure 7: Results from Pontos measurements for test CD12_R_01 (squared arrangement of 12 mm dowels; (a) red: bending deformation, blue: crushing deformation; (b) bending deformation of single dowels over relative rotation of the connection; (c) direction of dowel deformations over relative rotation of the connection (blue lines represent crushing deformation and red lines bending deformation); (d) crushing deformation over relative rotation of the connection.

Figure 8: Results from Pontos measurements for test BD12_U_02 (circular arrangement of 12 mm dowels; (a) red: bending deformation, blue: crushing deformation; (b) bending deformation of single dowels over relative rotation of the connection; (c) direction of dowel deformations over relative rotation of the connection (blue lines represent crushing deformation and red lines bending deformation); (d) crushing deformation over relative rotation of the connection.

Figure 9: Results from Pontos measurements for test ED20_R_02 (squared arrangement of 20 mm dowels; (a) red: bending deformation, blue: crushing deformation; (b) bending deformation of single dowels over relative rotation of the connection; (c) direction of dowel deformations over relative rotation of the connection (blue lines represent crushing deformation and red lines bending deformation); (d) crushing deformation over relative rotation of the connection.

Figure 10: Results from Pontos measurements for test FD20_R_01 (circular arrangement of 20 mm dowels; (a) red: bending deformation, blue: crushing deformation; (b) bending deformation of single dowels over relative rotation of the connection; (c) direction of dowel deformations over relative rotation of the connection (blue lines represent crushing deformation and red lines bending deformation); (d) crushing deformation over relative rotation of the connection.

Figure 11: Bending vs. crushing deformation of single dowels with a diameter of 12 mm and 20 mm. (a) Dowels loaded parallel to grain; (b) Dowels loaded 45° to the grain and (c) Dowels loaded perpendicular to the grain. Thick lines represent mean values, while thin lines represent minimum and maximum values.

Figure 12: Visualization of surface strains parallel (ϵ_x) and perpendicular (ϵ_y) to the grain, as measured on the surface of the LVL; (a) connection with 12 mm dowels *BD12_U_02* at $M_{global}=15.6$ kNm and (b) connection with 20 mm dowels *FD20_R_01* at $M_{global}=44.5$ kNm.

Figure 13: Visualization of surface strains (strains parallel, ϵ_x , and perpendicular, ϵ_y , to the grain and shear strains, ϵ_{xy}).

(a)

(b)

(c)

Figure 14: Inspection of specimen *BD12_U_01* (circular arrangement of 12 mm dowels); (a) deformed dowels, (b) inclination of deformed dowels, (c) compression of the LVL due to the embedment of steel dowels.