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DUCTILE BEHAVIOR OF DOWEL FASTENERS IN TIMBER STRUCTURES

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Abstract

As an important part of the seismic design, the ductile behavior of the timber structures is becoming more and more of interest. With respect of the capability of the connections to form plastic hinges within timber structures, an axial loaded joint of dowel fasteners in composite timber beam is examined in test conducted during COST Action FP1004 in 2012. This article analyzes the test results and provides additional study of a classical yield theory model of the reinforced dowel connection to describe the expected ductile behavior.

Key words: *timber structures, dowel connection, ductility, selftapping screws, reinforcement*

1.INTRODUCTION

The properties of timber and variuos wood based products lead to brittle behaviour and anisotropic nature of wood in certain loading models. On the other hand, dowel type joints in timber structures, which are frequently used in timber strucutres show high ductility when properly designed.

On a local level, timber has generally low deformation capacity and often displays brittle type behaviour. The response depends strongly on direction and type of loading. When loaded in tension, shear or bending the response is brittle with very little deformation capacity. Fracture energy dissipation in tension and shear is normally negligible in relation to the ductility required for robustness. The weakness in tension perpendicular to grain makes it necessary to use some type of reinforcement if ductility is desired.

Some types of engineered wood products have slightly more advantageous properties from ductility point of view, but in general loading models involving tension show limited ductility.

Because timber as a natural material is not able to form plastic hinges, the ductutile element in the structural system is introduced by joints performed with mechanical fasters.

Dowelled joints transfer forces through shear in mechanical fasteners mounted at an angle to the force direction. The most common fastener typre for timber elements worldwide. Dowel-type connections involve: nails, screws, dowels, nail plates and punched metal plate fasteners, bolts.

2. BASIC CHARACTERISTICS OF DOWEL JOINT CONNECTIONS

2.1. JOINTS WITH DOWEL-TYPE FASTENERS

Joints with dowel-type fasteners are the most common joints in timber structures. The benefits of this type of conncedtion can be summurized to: easy and less time – consuming to realise even at building site, non contolled environment in production is required, show ductile bevavior.Dowel-type connections can be designed to be ductile, which ensuares a safe structure. The load-carrying capacity, which can be calculated according to Johansen´s yield theory, is limited by the embedding strength of the timber, by the yield moment of the dowel-type fasteners and finally by the geometry of the connection.

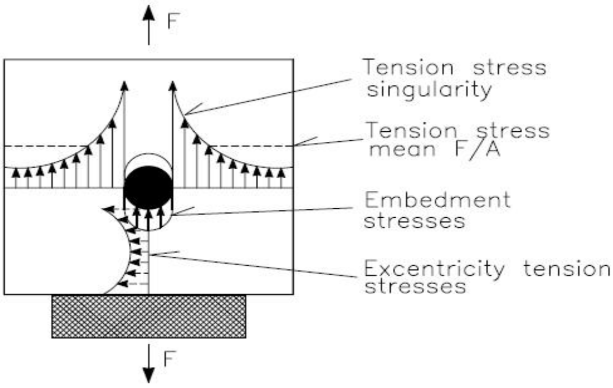

Figure 1: Schematic stress condition in a transverse section in dowel proximity, with attention to tension stresses.

2.2 JOINTS WITH SLOTTED – IN STEEL PLATES

Using steel plate as one of the members in timber joint is very common. Theoretically, this has the consequence that the forming of the plastic hinge is always located at timber-steel interface. This increases the capacity of the joint compared to timber-to-timber connections. There is a condition on the thickness of the steel plate to enable forming of a plastic hinge:

$$-\boldsymbol{t_{steel}} \geq \boldsymbol{d} \rightarrow \textbf{fixed support preventing forming of a plastic hinge}$$

$$-\boldsymbol{t_{steel}} \leq \boldsymbol{0.5d}$$
$$\rightarrow \textbf{pinned support and the dowel merely rotate in the hole without forming a plastic hinge}$$

Steel plates in structures subjected to fire must be protected e.g. by fire proof pair or coverege with wood. The last is done by making slots into timber members and inserting in the steel plates. Holes for dowels are pre-drilled both in wood and steel and the dowels are inserted in the holes to complete the connection.

2.2.1 Double shear connections

In joints with slotted – in steel plates location of plastic hinges is always at the steel-timber interface. Furthermore, the condition for the thickness of the steel plate need not to be fulfilled. A plastic hinge will form regardless of the thickness of the steel plate due to symmetry in the loading situation. However, the steel plate must be thick enough to withstand the embedding pressure from the dowel. Most engineering methods for the design of bolted or nailed joints in timber are based on the Johansen's yielding theory (1949) (EC5, 1993) (Aune et al., 1986) which assumes plasticity in both the wood and the fastener. Some recommendations exist in design codes in order to avoid brittle failure in connections, but they are essentially based on empirical rules.The design recommendations for multiple fasteners joints are generally based on the response of the single bolt joint.The resistance for joint with slotted –in central steel plate and the kinematically possible failure modes are shown in Table 1:

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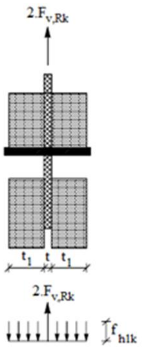
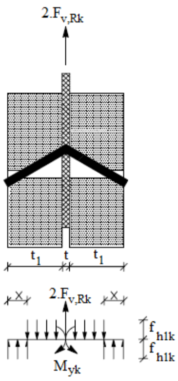
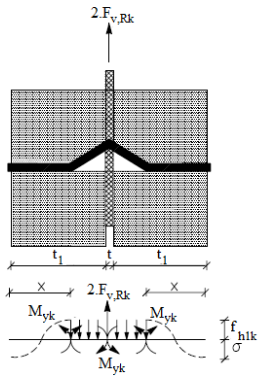
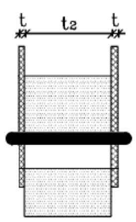
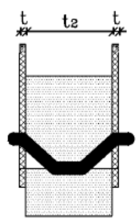
Table 1: The three possible plastic failure modes for a double shear dowel connector used with a central steel plate.

		
$F_{v,Rk} = f_{h1k} t_1 d$	$F_{v,Rk} = f_{h1k} t_1 d \left(\sqrt{2 + \frac{4M_{yk}}{f_{h1k} d t_1^2}} - 1 \right)$	$F_{v,Rk} = \sqrt{2} \sqrt{2 M_{yk} f_{h1k} d}$
Mode 1: the dowel is dragged through the wood that yields plastically	Mode 2: failure is realized when the embedment stresses act on the dowel over a sufficient length to form a plastic hinge in the dowel. The hinge is formed at the location of the steel plate and the dowel rotates as a stiff member in the wood.	Mode 3: failure is realized when the stress on the dowel acts over sufficient length x to form an additional plastic hinge in the dowel.

2.2.2 Multiple shear connections

Multiple shear connections using slotted in steel plates are widely used in modern timber constructions. In the Eurocode 5 the load bearing formulas are not explicitly given for more than two shear planes. For higher number of shear planes it is recommended to calculate the capacity as the lowest load carrying capacities for each shear plane, taking each shear plane as part of a series of double shear connections:

Table 2: Load bearing capacity of double shear steel-to-timber joints according Eurocode 5

	
Double shear steel-to-timber joints where $t_{steel} \geq d$	

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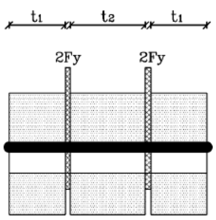
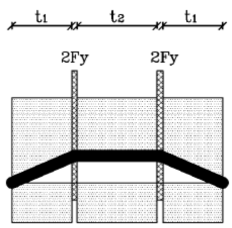
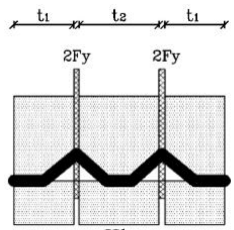
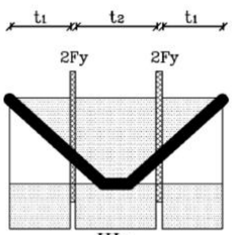
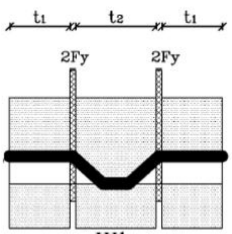
$F_{v,Rk} = 0.5 f_{h2k} t_2 d$	$F_{v,Rk} = 1.5\sqrt{2 M_{yk} f_{h2k} d}$
Double shear steel-to-timber joints where $t_{steel} \leq 0.5d$	
$F_{v,Rk} = 0.5 f_{h2k} t_2 d$	$F_{v,Rk} = 1.1\sqrt{2 M_{yk} f_{h2k} d}$

This procedure is of course conservative for all failure modes that benefits from the rotational restriction of the dowel in the section between the fictitious double shear connections. Load bearing formulas can be derived from the kinematically possible failure modes as shown in Table 3 for a connection with slotted in steel plates and four shear planes:

Table 3: Kinematically possible failure mode in a connection with slotted in steel plates and four shear planes.

 I	 IIa	 IIb
$F_{v,Rk} = \frac{1}{4}(2t_1 + t_2) d f_{h2k}$	$F_{v,Rk} = \left(-\frac{t_1}{2} + \frac{t_2}{4} + \sqrt{\frac{t_1^2}{2} + \frac{M_{yk}}{d f_{h2k}}}\right) d f_{h2k}$	$F_{v,Rk} = \sqrt{4 M_{yk} d f_{h2k}}$

 IIIa	 IIIb
$F_{v,Rk} = \left(\frac{t_1}{2} + \frac{1}{2}\sqrt{t_1^2 + \frac{2M_{yk}}{d f_{h2k}}}\right) d f_{h2k}$	$F_{v,Rk} = \left(\frac{t_1}{2} + \sqrt{\frac{M_{yk}}{d f_{h2k}}}\right) d f_{h2k}$

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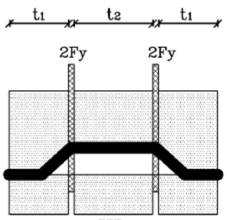
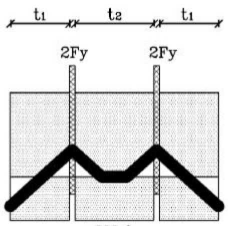
 IIIc	 IIId
$F_{v,Rk} = \left(\frac{t_2}{4} + \sqrt{\frac{M_{yk}}{df_{h2k}}}\right) df_{h2k}$	$F_{v,Rk} = \left(-\frac{t_1}{2} + \sqrt{\frac{t_1^2}{2} + \frac{M_{yk}}{df_{h2k}}} + \sqrt{\frac{M_{yk}}{df_{h2k}}}\right) df_{h2k}$

The extra load bearing capacity gained when using calculations in Table 3 compared to the procedure suggested in the Eurocode 5 can only be evaluated given the material parameters. Then it is possible to optimize the geometry benefitting from the rotational restriction in the central section.

2.3 WOOD REINFORCEMENT

An approach to preventing brittle failure in connections is to enhance the brittle capacity by means of reinforcement.

There are series of tests on wood reinforced with glass fibres glued to the side of the wood members with a polyester glue. The finding is for dowels that the ductility is increased and a marginal strength increase is observed and the spacing requirements can be reduced when using reinforced members compared to unreinforced. This observation corresponds to an increase in the brittle strength of the wood members obtained by the reinforcement. For nails the strength is increased more than 50 % probably because the reinforcement prevents the nails from leaving the wood in the embedment zone.

Similar findings are reported when using wood densification to enhance the connector performance. Generally, the increase in strength properties follows the degree of densification.

The easier methods for reinforcement are to drive screws parallel to loading direction. In this method, the screws work as piles to transmit compression stress to inner part of the wood.

3. DESCRIPTION OF THE CONDUCTED EXPERIMENT WITH DOWEL JOINT CONNECTIONS

Three sets of dowel-type timber connections with slotted-in steel plates are tested. Two steel plates having a thickness of 8 mm are inserted between 45 mm thick timber boards. The cross section of the timber boards is 45x140 mm2. The steel plates and the timber are connected with 12 mm dowels inserted into 12.5 mm pre-drilled holes. There are three variations of the connections each of which is tested 3 times for a total of 9 tests; these are shown in Figure 3 a, b, c. The grade of the timber is C24 and the steel quality of the plates is S235. The connections are designed asymmetrically such that one side of the connection is weaker than the other. The stronger side of the connection is the same for all cases and consists of 6 M12-8.8 dowels with a length of 200 mm. Failure is this expected at the weak side of the connections which vary according to the next sections.The experiments are conducted in a tensile MTS machine in which force and overall displacement is measured (the tests are displacement controlled).

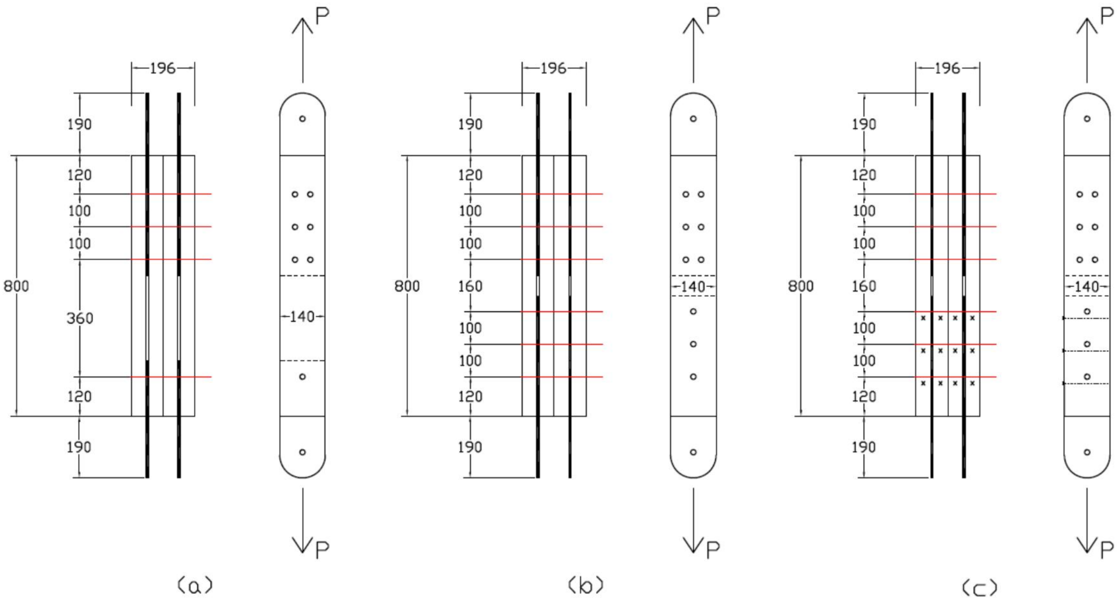


Figure2. Experimental setup of dowel connections: (a) single dowel, (b) 3 dowels & (c) 3 dowels w/ strengthening screws

3.1. Setup 1U – Single dowel connection

The first setup consists of a connection with a single M12-4.8 dowel. The specifications for the experiments are given in Table 4:

Table 4: Specifications for testing of un-strengthened single dowel steel-timber connections

Test No.	Test Speed (mm/s)	Time to failure (min)
1U1	0,10	6.5
1U2	0,10	5
1U3	0,125	3.5

3.2. Setup 3U – 3- dowel connection

The second setup consists of a connection with 3 M12-4.8 dowels. The specifications for the experiments are given in Table 5:

Table 5: Specifications for testing of un-strengthened 3-dowel steel-timber connections

Test No.	Test Speed (mm/s)	Time to failure (min)
3U1	0,10	4
3U2	0,10	4
3U3	0,125	2.5

3.3 Setup 3R – 3-Dowel connection (reinforced)

The third and final variation of the dowel connection test consists of 3 M12-4.8 dowels in which the boards are locally strengthened using reinforcing screws in the timber to help prevent splitting. The strengthening screws are of type SFS, WT-T 6,5x 130. The specifications for the experiments are given in Table 6:

Table 6: Specifications for testing of reinforced 3-dowel steel-timber connections

Test No.	Test Speed (mm/s)	Time to failure (min)
3R1	0,10	8
3R2	0,10	6
3R3	0,15	4

4. DISCUSION ON THE EXPERIMENTAL RESULTS

The results from the conducted experiments are summarized on the following graphics.

For each experimental setup is done theoretical estimation of the resistance of the joint with slotted – in steel plates for kinematically possible failure modes in accordance with the procedures in Eurocode 5 and the Johansen's yield theory shown in Table 2. This theoretically estimated resistance is also snown on the following graphics.

Here, the load-carrying capacity, which can be calculated according to Johansen´s yield theory, is limited by the embedding strength of the timber, by the yield moment of the dowel-type fasteners and finally by the geometry of the connection.

The spacing of dowel-type fasteners affects the splitting tendency of timber in the connection area. The splitting tendency increases with decreasing fastener spacing parallel to the grain and hence decreases the effective number of fasteners n_{ef}.

A number of researches on the embedding strength of timber reported high correlations between the maximum embedding load and the timber density and the results of these works are reflected in the European standard for determining embedding strength, BS EN 383:1993 and in the Eurocode 5 timber design code.

In addition to fastener sizes and wood species, there are quite a few other factors that affect embedding strength, such as slenderness and surface condition of fastener, orientation of fastener with respect to timber grain, degree of initial contact between fastener and wood, etc.

The tested species are timber grade C24 and for dowels up to 30 mm diameter the following characteristic embedding strength values is used, at an angle $\alpha = 0°$ to the grain:

$$f_{h,0,k} = \frac{f_{h,0,k}}{k_{90}\sin^2\alpha + cos^2\alpha} = \frac{0{,}082.(1-0{,}01d)\rho_k}{1} = \frac{0{,}082.(1-0{,}01.12).350}{1}$$

$f_{h,0,k} = 25{,}256\ N/mm^2$

For dowel - $d = 12\ mm$, S235, the characteristic value for the yield moment is:

$$M_{y,k} = 0{,}8.f_{u,k}.\frac{d^3}{6} = \frac{0{,}8.360.12^3}{6} = 82944\ Nmm$$

Setup 1U: 1 dowel – connection: tension parallel to the grain

The tested connection is a multiple – shear connection and according to the procedure suggested by Eurocode 5, theoretical characteristic resistance of the joint can be estimated as a sum of the load bearing capacity for joint with slotted –in central steel plate x 2 (estimated according to Table 1) and the load bearing capacity of double shear steel-to-timber joint (estimated according to Table 2).

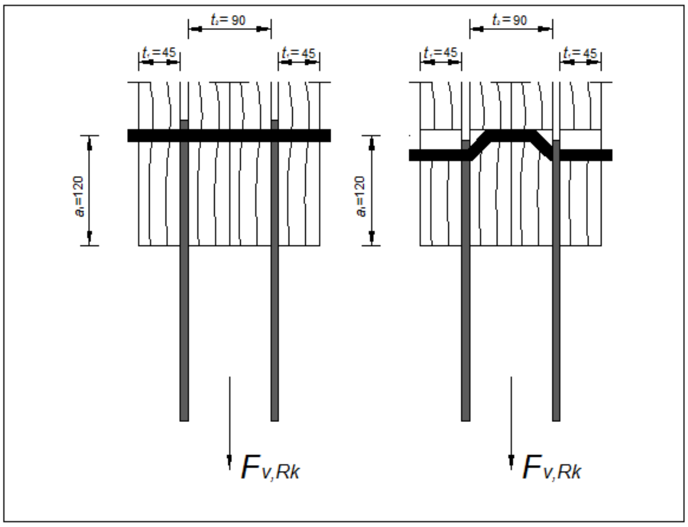


Figure 3. Test Setup 1U – 1-Dowel connection

For the two different double-shear timber – steel connections : $t_1 = 45\ mm$ and $t_2 = 90\ mm$.

If the theoretical estimation of the resistance of the joint is done according to the procedure of Eurocode 5:

$$F_{v,Rk} = 2.F_{v,Rk,1} + 2.F_{v,Rk,2} + 2.F_{v,Rk,1}$$

$$F_{v,Rk} = f_{h1k}t_1 d\left(\sqrt{2+\frac{4M_{yk}}{f_{h1k}.d.t_1^2}}-1\right) + 2.1{,}23\sqrt{2M_{yk}f_{h2k}d} + f_{h1k}t_1 d.\left(\sqrt{2+\frac{4M_{yk}}{f_{h1k}.d.t_1^2}}-1\right)$$

$$F_{v,Rk} = 52{,}46 \text{ kN}$$

Another procedure is suggested in Table 3. Following the predicted with Johansen's yield theory behavior of the dowel (as shown on Figure 3b) the estimated failure mode is IIb (Table 3) and the theoretical estimation of the resistance of the joint is:

$$F_{v,Rk} = 6.\sqrt{4M_{yk}df_{h2k}} = 6.10{,}027 = 60{,}165\ kN$$

Because the specimens were tested with an end distance $a_2 = 120\ mm > 7.d = 84\ mm$ no premature failure in splitting or shear plug is expected.

The tested specimens showed expected failure mode for setup 1 with applied tension load parallel to the grain:

At first slip of the connection increases due to the difference in the hole and dowel diameters, than the dowel is dragged through the wood that yields plastically and the embedment load increases almost linearly with increasing slip. Later first plastic hinge is formed in the dowel and the embedment load increases almost linearly with increasing slip until sudden longitudinal splitting commences. The load drops somewhat, but increases further almost linearly with displacement, at close to zero slope, as more plastic hinges in the dowel are formed, the longitudinal cracks grow and more wood gets crushed underneath the fastener until final longitudinal splitting commences.

The test results showed good comparability between the theoretically estimated resistance of the joint and the test results for it.

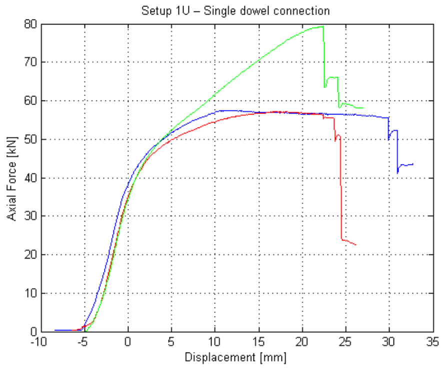


Figure 4. Test Setup 1U – 1-Dowel connection, results

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Setup 3U: 3 dowel – connection, unreinforced : tension parallel to the grain

When analyzing the load carrying capacity of a connection with multiple dowels parallel to the grain predicting the performance by the number of dowels does not present the true behavior in many cases. Hence the effective number of fasteners n_{ef} must be considered.

According to Eurocode 5:

$$n_{ef} = min\begin{cases} n \\ n^{0.9}.\sqrt[4]{\dfrac{a_1}{13d}} \end{cases} = min\begin{cases} 3 \\ 2.40 \end{cases}$$

Hence for one row of 3 fasteners parallel to the grain direction the expected characteristic load carrying capacity should be taken as:

$$F_{v,ef,Rk} = n_{ef}.F_{v,Rk} = \begin{cases} 2{,}40.60{,}165 = 144{,}4\ kN - \text{procedure of failure mode IIIa (Table 3)} \\ 2{,}40.52{,}46 = 125{,}9\ kN - \text{procedure of Eurocode 5} \end{cases}$$

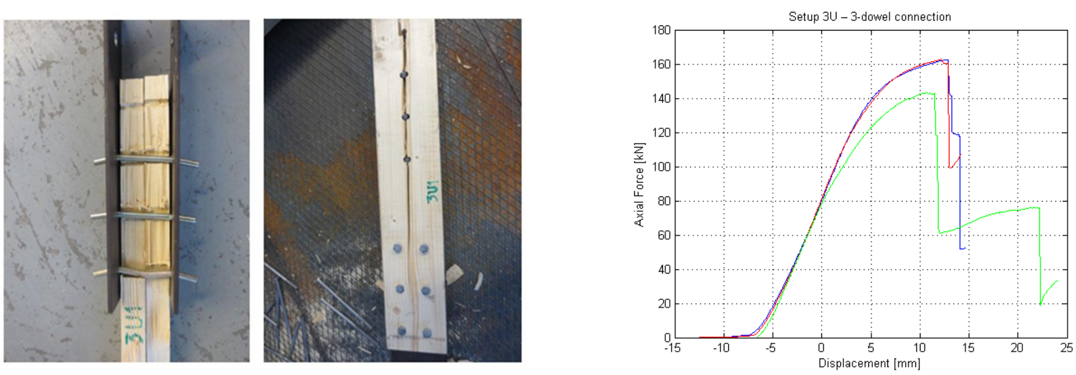


Figure 5. Test Setup 3U – 3-Dowel connection, unreinforced - results

Setup 3P: 3 dowel – connection, reinforced : tension parallel to the grain

The spacing of dowel-type fasteners affects the splitting tendency of timber in the connection area. The splitting tendency increases with decreasing fastener spacing parallel to the grain and hence decreases the effective number of fasteners n_{ef}. Splitting may be prevented by reinforcing the connection area and, consequently, the effective number n_{ef} of fasteners increases. Self-tapping screws with continuous threads represent a simple and economic reinforcement method. In connections with sufficient reinforcement between the dowels, the timber does not split and the effective number n_{ef} equals the actual number n of dowels.

For this test the screws are placed between the dowel-type fasteners, both perpendicular to the dowel axis and to the grain direction.

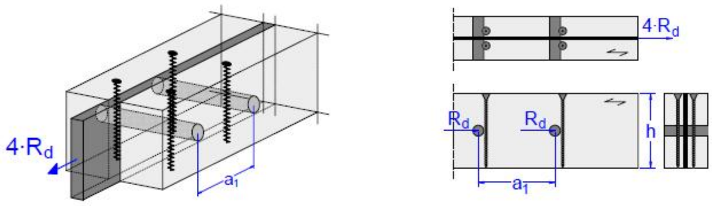


Figure 6. Reinforced connection using self-tapping screws placed in contact with the dowels

Both effects – preventing splitting and increasing the load-carrying capacity by placing the screws in contact with the dowels – may cause an increase of up to 120% of the load carrying capacity compared to non-reinforced connections (Figure 5).A calculation model as an extension of Johansen´s yield theory and based on theoretical and experimental studies is presented.The load-carrying capacity for reinforced connections is derived on the basis of the same assumptions as Johansen´s yield theory. The screws, placed in contact with the dowel-type fasteners, perpendicular to the dowel axis and to the grain direction are loaded just as the dowels themselves perpendicular to their axis. One of the basic assumptions in Johansen´s yield theory is an ideal rigid-plastic material behavior of the timber in embedding and of the fastener in bending. Under this assumption, screws as reinforcements loaded perpendicular to their axis also show an ideal rigid-plastic load carrying behavior (Figure 7).Consequently, the screw only moves in force direction, when the dowel load component F_{VE} reaches the load-carrying capacity R_{VE} of the screw. In this case, the screw represents a "soft" support. Alternatively, for $F_{VE} < R_{VE}$, the screw does not move and represents a rigid support for the dowel. This consideration leads to four sub-failure modes for each failure mode in timber-to-timber connections and two sub-failure modes for each failure mode in steel-to-timber connections in Johansen´s yield theory. Subsequently, the sub-failure modes for reinforced steel-to-timber and timber-to-timber connections are presented.

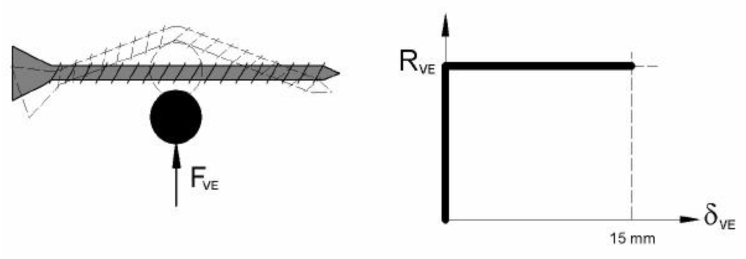


Figure 7. Assumed load-carrying behaviour of a screw as reinforcement loaded perpendicular to the axis

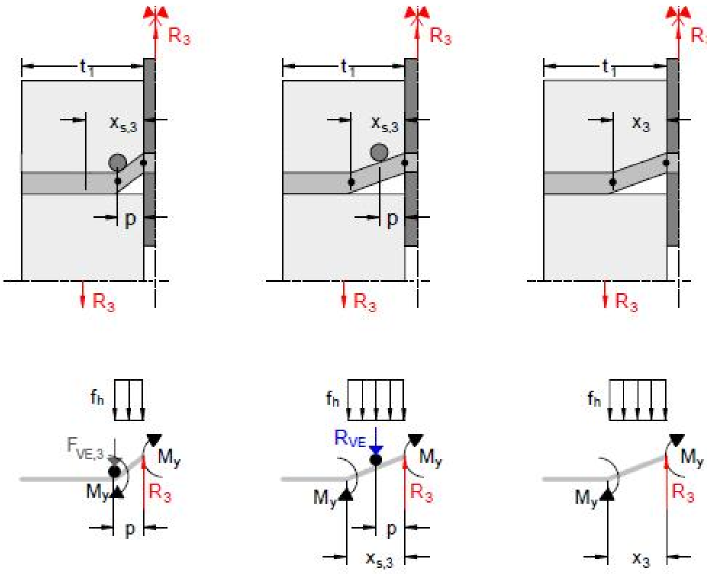
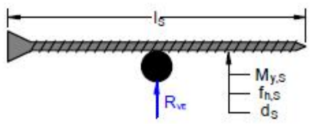


Figure 8. Reinforced connection with sub-failure mode "rigid", reinforced connection with sub-failure mode "soft" and non-reinforced connection

The load-carrying capacity R of reinforced connections is calculated depending on the load carrying capacity $R_{i,VE}$ of the reinforcing screws. $R_{i,VE}$ is derived and calculated according to Johansen´s yield theory as for steel-to-timber connections with inner steel plates. For the case of one dowel-type fastener being reinforced by one screw (Figure 11), the load-carrying capacity R_{VE} follows as:

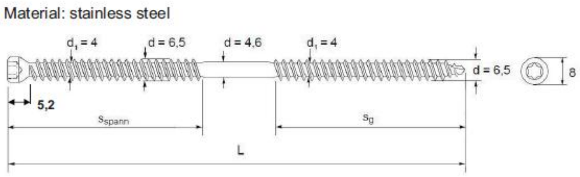


$$R_{VE} = \min\{R_{A1}, R_{A2}, R_{A3}\}$$

Figure 9. One dowel-type fastener reinforced by one screw

For used in the experiment strengthening screws of type:

SFS, WT-T 6,5x 130:



$$My, s = 7000\ Nmm$$

$$f_{h,s} = \frac{f_{h,0,k}}{k_{90} \sin^2 \alpha + cos^2\alpha} = 27{,}55\ N/mm^2$$

$$d_s = 4\ mm$$

$$l_s = 130\ mm$$

$$R_{A1} = f_{h,s}.d_s.l_s = 14{,}327\ kN$$

$$R_{A2} = f_{h,s}.d_s.l_s.\left[\sqrt{\frac{16.M_{y,s}}{f_{h,s}.d_s.l_s^2} + 2} - 1\right] = 6{,}236\ kN$$

$$R_{A3} = 4.\sqrt{M_{y,s}.f_{h,s}.d_s} = 3{,}513\ kN$$

Hence, $R_{VE} = min\{R_{A1}, R_{A2}, R_{A3}\} = 3{,}513\ kN$.

If the distance from screw to dowel is larger than the distance between shear plane and the plastic hinge – $p > x_{2,3}$ ($p = \frac{45}{2}\ mm$) no reinforcement occurs (as shown on Figure 8).

Therewith, the load-carrying capacity for reinforced steel-to-timber connections with an inner steel plate can be calculated as follows:

$F_{v,Rk,1} = min\{R_1, R_2, R_3\}$ – for the three possible failure modes I,II,III.

For failure mode I:

$$R_1 = f_{h1k}.d.t_1 + R_{VE} = 17{,}151\ kN$$

For failure mode II:

$$x_2 = \sqrt{\frac{t_1^2}{2} + \frac{M_{yk}}{f_{h1k}.d}} = 35{,}86\ mm > p$$

$$F_{VE,2} = \frac{M_{yk}}{p} + \frac{f_{h1k}.d}{p}.\left[\frac{t_1^2}{2} - p^2\right] = 30{,}838\ kN > R_{VE}$$

Then $R_2 = R_{VE} + f_{h1k}.t_1.d.\left[\sqrt{2 + \frac{4}{t_1^2}.\left(\frac{M_{yk} - R_{VE}.p}{f_{h1k}.d}\right)} - 1\right] = 9{,}284\ kN$

For failure mode III (Figure 10):

$$x_3 = \sqrt{\frac{4.M_{yk}}{f_{h1k}.d}} = 33{,}1\ mm > p$$

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$$F_{VE,3} = \frac{2M_{yk}}{p} - \frac{f_{h1k}.d.p}{2} = 3{,}963\ kN > R_{VE}$$

$$R_3 = R_{VE} + \sqrt{2}.\sqrt{f_{h1k}.d.(2M_{yk} - R_{VE}.p)} = 10{,}695\ kN$$

Hence load carrying capacity of reinforced connection steel to - timber connections with an inner steel plate is derived:

$$F_{v,Rk,1} = min\{R_1, R_2, R_3\} = R_2 = 9{,}284\ kN$$

Similarly the load carrying capacity of reinforced connection steel to - timber connections with an outer steel plate is derived:

$$F_{v,Rk,2} = min\begin{Bmatrix} 0{,}5.f_{h1k}.d.t_2 + R_{VE} \\ R_{VE} + \sqrt{2}.\sqrt{f_{h1k}.d.(2M_{yk} - R_{VE}.p)} \end{Bmatrix} = 10{,}695\ kN$$

The total expected characteristic load carrying capacity for the 3-dowel reinforced connection should be taken as:

$$F_{v,Rk} = n.\left(2.F_{v,Rk,1} + 2.F_{v,Rk,2} + 2.F_{v,Rk,1}\right) = 175{,}582\ kN$$

As shown on the Figure 8 below the test results correspond to the expected characteristic load carrying capacity and ductile behavior of the connection.

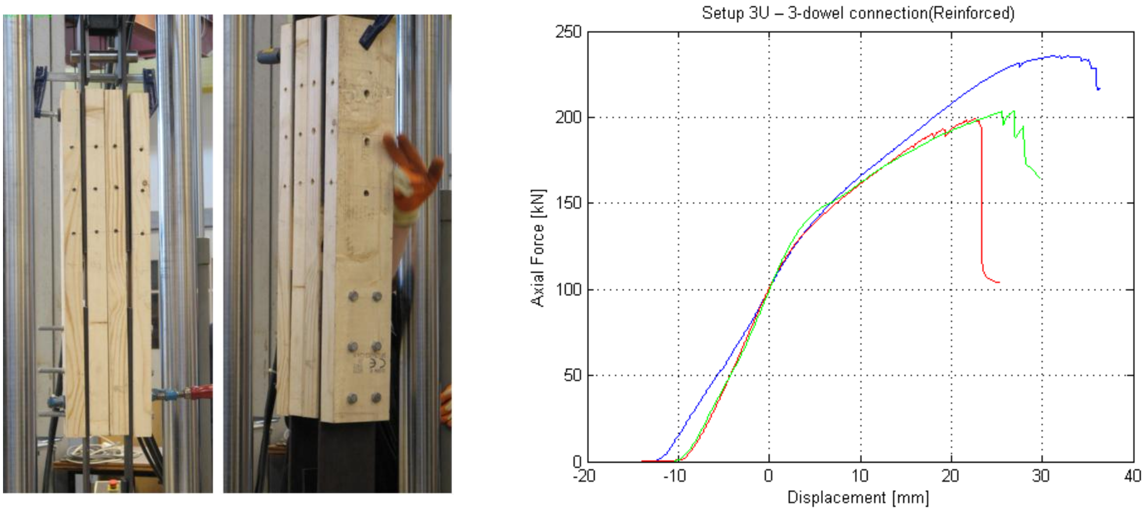

Figure 10. Test Setup 3P – 3-Dowel connection, reinforced - results

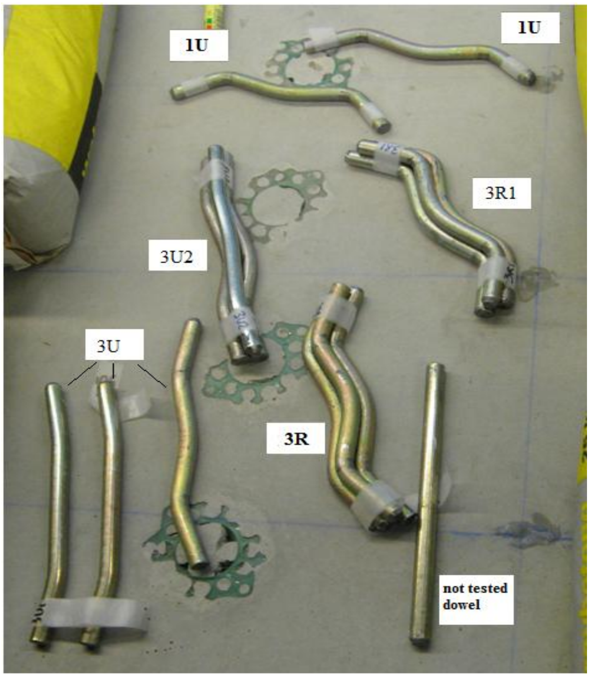

Figure 11. Test results from the three setups – the deformed shapes of the tested dowels

On Figure 11 are shown the deformed dowels from the conducted tests, named corresponding to the test setup. Following the predicted ductile behavior was fulfilled since the dowels from the three setups 1U, 3U and 3R developed plastic hinges and later growing longitudinal cracks and crushed wood underneath the fasteners were growing until final longitudinal splitting commenced.

As general the deformed shapes of the dowels follow the failure mode IIb (Table 3) described by the Johansen's yield theory.

However, the fasteners in the unreinforced Setup 3U: 3 –dowel connection did not developed the expected plastic hinges due to premature drop of the embedding strength caused by splitting in timber. The test results showed that in calculation of the load carrying capacity must be used n_{ef} instead of n. Therefore reinforcement of the connection must be applied to prevent splitting of timber and to allow fully ductile behavior of the dowel fasteners.

4. CONCLUSION

Self-tapping screws with continuous thread represent a simple and economic method to reinforce connections where the timber is prone to splitting. In connections with sufficient reinforcement between the dowels, the timber does not split and the effective number n_{effe} equals the actual number n of dowels. Furthermore, by placing the screws in contact with the dowel-type fasteners, the load-carrying capacity and the stiffness of a connection increases.

This reinforcing method causes an increase of the load-carrying capacity with up to 40% compared to non-reinforced connection with a ductile load-carrying behavior. Values were verified by tests.

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