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Investigations of connection detailing and steel properties for high ductility doweled timber connections

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ABSTRACT

According to Eurocode 8 moderate to high dissipative behaviour of timber structures requires sufficient ductility of the critical regions. Earlier experiments on timber connections with slotted-in steel plates and laterally loaded common steel dowels rarely achieved high ductility values. Connections consisting of LVL-C members, dowel-type fasteners with different post-elastic steel properties, full confinement of the timber member and measures to restrain the notch effect were investigated by means of monotonic and cyclic tests with regards to the displacement ductility. The measures taken proved to be effective in enhancing the plastic deformation capacity of the steel dowels to a large extent. However, a new aspect was observed: the constriction of the dowels in the contact area with the plate. The research results provided a better understanding of the factors influencing the behaviour of slotted-in steel plate connection.

1. Introduction

Due to an unfavourable relationship between the behaviour factor q (or the Action Reduction Factor according to other international codes) and the overstrength factor γ_{Rd} (see e.g. [1,2,3,4,5,6]) capacity design of timber structures is relatively unattractive. Connections with laterally loaded dowel-type fasteners generally combine low ductility with high overstrength. These two effects have a negative impact on the capacity design. On one hand, the low ductility limits the value of the behaviour coefficient q and on the other hand the high overstrength values [7,8,9,10] inevitably leads to high overstrength factors γ_{Rd}. What is gained through the behaviour factor q is almost immediately lost through the over-strength factor γ_{Rd} to be applied for the capacity design of the non-dissipative zones. When the behaviour coefficient q is relatively low ($q \leq 3$), the capacity design of non-dissipative zones may lead to design forces which are higher than the ones resulting from an elastic analysis. This is often the case in low to medium seismicity regions where wind becomes the governing action for the design of the bracing system. For this reason, in the revision of Eurocode 8 [4] it is recommended that in Ductility Class Medium (DC2) the design forces in the non-dissipative connections, need not be taken as greater than the values obtained from an analysis made considering a completely elastic behaviour ($q = 1$).

The low displacement ductility of timber connections made with dowel-type fasteners is mainly due to the steel quality generally used and to the insufficiently effective detailing measures. Differently from the steel quality prescribed for ductile walls in reinforced concrete [11,12,13], only a minimum tensile strength f_u is required and nothing is specified for the post-elastic properties [14,15]. The design details are limited to the spacings and thicknesses of timber members according to the European Yielding Model (or Johansen equations). As a consequence, certain values required by the standards (e.g. [1,5]) simply cannot be achieved by the connections commonly available today. Furthermore, serial yielding does not occur systematically [16,17]

A previous test campaign showed that using a steel grade with a high strain hardening ratio k_s allowed serial yielding, although not fully [17]. However, the obtained ductility did not reach the desired high values and it seemed that the potential of a steel with favourable post-elastic properties was not fully exploited. It was therefore assumed that it was the notch effect caused by the plate on the dowel that prevented high ductility values from being achieved. Indeed, if the strength of the slotted-in plate steel is higher than that of the dowels and the holes are sharp-edged (which is usually the case), the plate acts on the dowel like a wire cutter. Therefore, two notch-effect restraining measures were then

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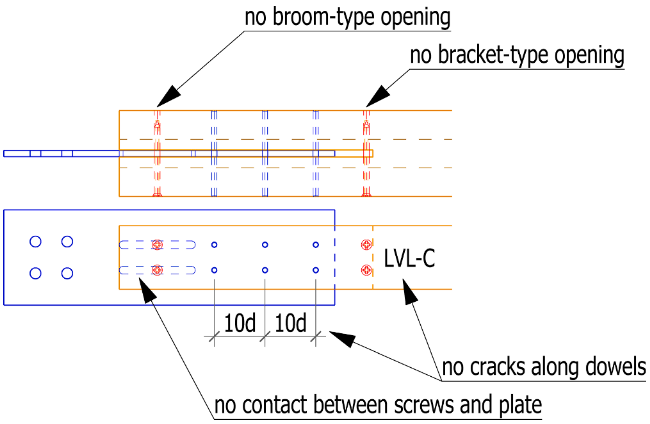


Fig. 1. Confinement of timber member.

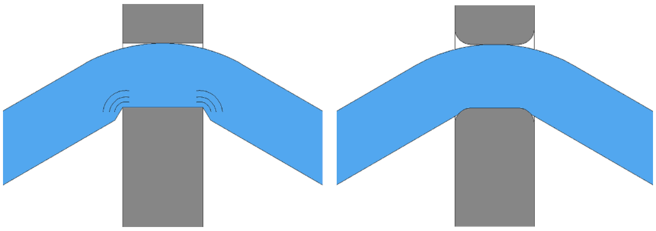


Fig. 2. Notch effect in the left figure and notch effect restrained in the right figure.

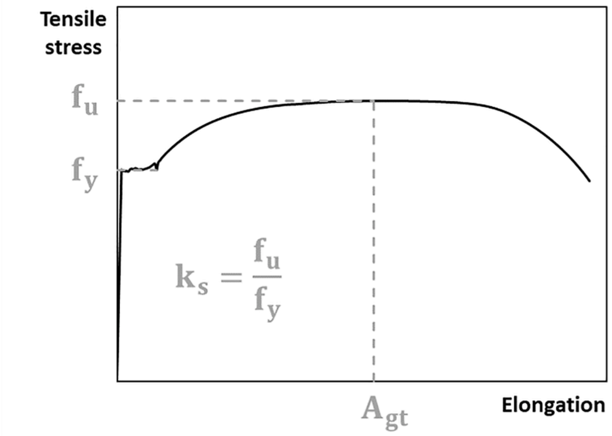


Fig. 3. Designation of the post-elastic steel properties.

proposed [17]:

$$\text{Hierarchy of the strengths}: f_{u,plate} \leqslant 0.8 f_{y,dowel} \tag{1}$$

$$\text{Rounding of the steel plate hole edges}: r_{min} \geqslant 0.2d \tag{2}$$

The present study investigates these notch effect restraining measures aiming to exploit the potential of a steel grade with favourable post-elastic properties to a large extent and, if possible, to increase the ductility of dowel-type timber connections significantly. This achievement would then make the capacity design of timber structures with dowel-type timber connections attractive.

The chosen methodology is described in the following. Firstly, a preliminary check of the notch effect restraining measures is carried out by means of a simple comparative test. As these proved to be effective, a more in-depth study of the effectiveness of the measures taken was conducted. This latter study led to the assumption that when full confinement is achieved and the notch effect is restrained, it is the elongation A_{gt} that determines the ductility of the connection. This assumption was finally investigated.

2. Background research and Eurocode requirements

2.1. Capacity design and code requirements

Doweled timber connections are often used as dissipative zones in different wooden structural systems in seismic prone areas, such as braced frame structures with dowel-type connections or moment-resisting frame structures [6]. According to the ongoing revision of the chapter for the seismic design of timber buildings of Eurocode 8 [5], when dowel-type mechanical connections are designed as dissipative zones, the less ductile failure modes should be designed with a safety margin with respect to the selected ductile failure mode providing energy dissipation. This means that, according to the failure modes defined in the European Yielding Model (or Johansen equations) for dowel-type steel-to-timber connections with internal steel plates, the connections should be designed in order to obtain a failure mode characterized by the formation of one or better two hinges in the mechanical fasteners.

In addition, some detailing rules are provided to avoid brittle failures due to splitting of wood caused by shrinkage perpendicular to the grain in the connection area. Among these, it is specified that provisions should be undertaken in order to avoid tension stresses perpendicular to the grain due to the restrained shrinkage of wood such as (i) the use of ovalized holes in the timber and metal plates, in order to allow the free movement of wood, (ii) the use of as few fasteners as possible, near to each other in a way not to restrain shrinkage of wood perpendicular to the grain and (iii) reinforcement in the connection region to resist the tension perpendicular to the grain due to the restrained shrinkage of wood.

Therefore, in order to capacity design dissipative connections made with dowel-type metal fasteners and internal steel plates, two concepts are of the outmost importance:

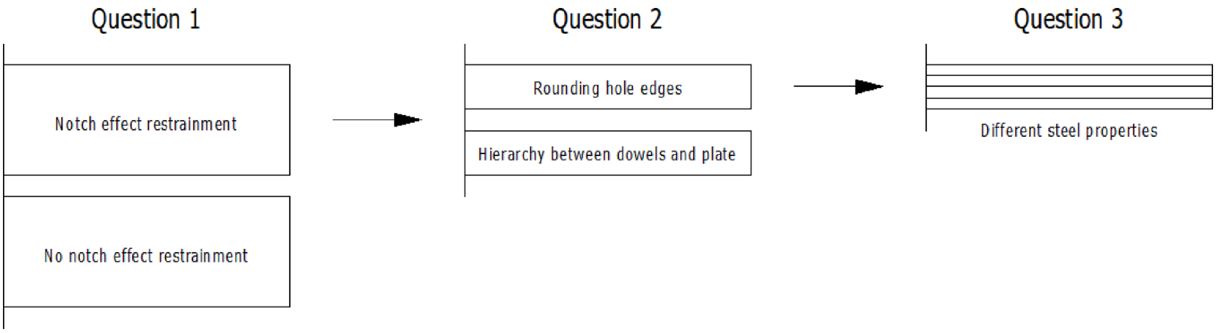


Fig. 4. Schematic approach of narrowing down the issues in questions.

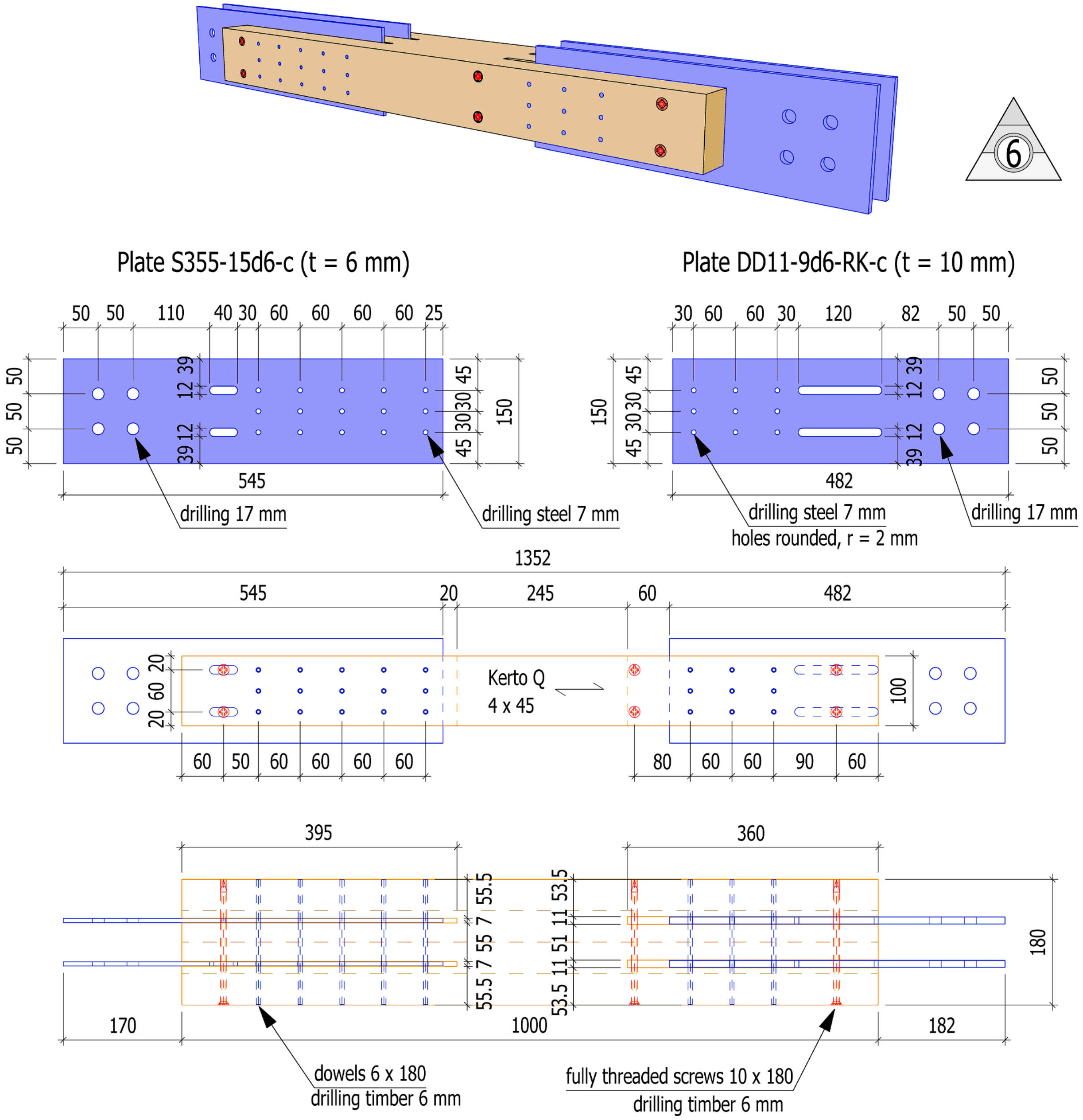


Fig. 5. Layout of specimens 4S-9d6-RK-c (LVL-C with confinement screws on one side of the dowel group, fixing connection on the left, tested connection with notch effect restraining measures on the right). The symbol left on the top means that both notch effect restraining measures have been taken.

- the connection failure mode should be as more ductile as possible, possibly with the formations of two plastic hinges in the mechanical fastener and
- brittle failure modes, especially those caused by tension perpendicular to the grain due to the restrained shrinkage of wood should be prevented.

However, according to experimental observation made in previous research [17], other measures could be undertaken in order to prevent brittle failures in timber members and enhance the ductile failure mode of dowel-type steel-to-timber connections, and precisely:

i. confinement of timber members,
ii. measures in order to restrain or prevent the notch effect and
iii. use of adequate steel grade with favourable post-elastic properties.

2.1.1. *Confinement of timber members*

Confinement of timber members is very important in order to prevent brittle failure modes in wood members with slotted-in steel plates. Besides the Eurocode 8 provisions described above, in such type of connections another effect which should be prevented is the opening of the joint with the separation of the two external timber sides when the dowel-type fasteners are transferring the load from the steel plate to the wood members.

Different details can be used to prevent such effect and keep the external wooden sides parallel to the steel plate surface. One possible solution, which was used in [27] is the use of large diameter (16 mm to 20 mm) steel bolts inserted perpendicularly in order to keep together the wooden members. Another possible solution, which was used in this research, is the use of fully threaded screws, usually of 8 mm to 12 mm diameter, inserted perpendicularly in over-sized holes in the steel plate.

The confinement in both lateral directions is ensured according to Fig. 1.

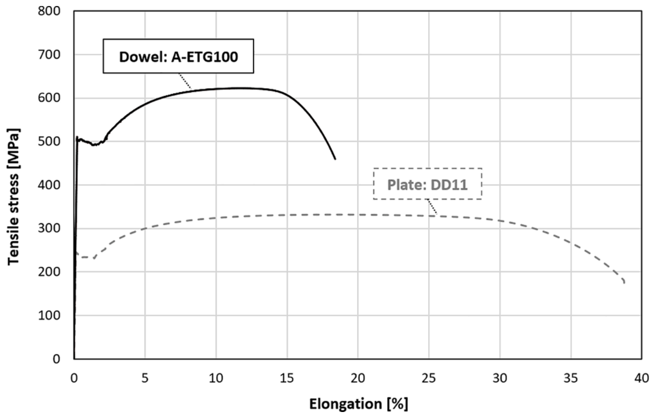


Fig. 6. Stress-elongation diagrams of the steel used for the dowel (A-ETG100) and for the plate (DD11).

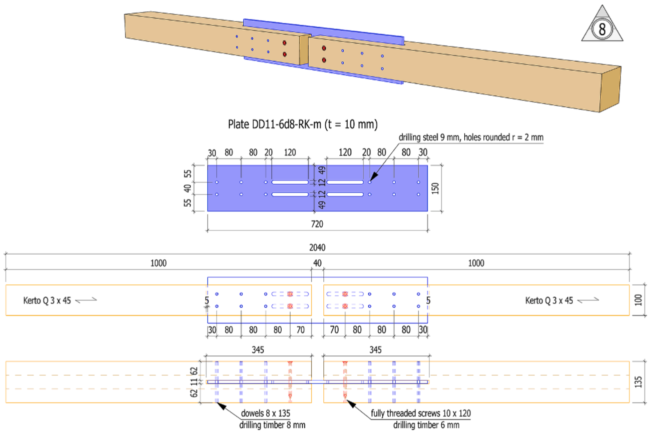


Fig. 7. Layout of specimens 2S-6d8-RK-m (LVL-C with confinement screws on one side of the dowel group, fixing connection on the left, tested connection with notch effect restraining measures on the right). The symbol means that both notch effect restraining measures have been taken.

2.1.2. Notch effect

The notch effect in dowel-type steel-to -timber connections made with slotted-in steel plates can be defined as the effect of stress peaks due to cross section reduction in the steel dowel-type fasteners resulting from sharp hole edges in the steel plates. The formation of a notch is shown in Fig. 2.

2.1.3. Steel properties

The properties of the steel used to manufacture dowels and steel plates have a large influence on the mechanical and dissipative properties of doweled steel-to-timber connections. The provisions given in most of the international design codes are mainly concentrated in providing limits to the steel strength (yield or ultimate) and almost no other provision can be found related to other properties of steel, such as the strain hardening k_s and the elongation at maximum stress A_{gt} (Fig. 3).

However, as already stated in [17], these properties have a large influence on the post-elastic behaviour of this type of connections.

2.2. Background research

The Authors couldn't find many references in literature of specific experimental or numerical investigations carried out in order to quantify the notch effect as defined above, however a large amount of research has been undertaken in order to investigate mainly other parameters like strength, stiffness and energy dissipation capacity. The notch effect was however observed in Ottenhaus et al. [18] and Brown and Li [32].

Shin and Smith [19] estimated the stress concentration factor K_t by means of a finite element method for fatigue crack growth in sharp elliptical edge notches. Schijve [20] used three different methods to calculate stress concentration factors of sharp edge notches and compared them with the numerical analysis conducted by Shin and Smith. Dundurs and Lee [21] analysed the effect of stress concentration at a sharp edge in contact problems with numerical analysis. Elliot et al. [22] investigated the effect of oversized holes in the behaviour and strength of bolted steel connections loaded in shear.

As for steel-to-timber connections, studies were mainly concentrated on the evaluation of different parameters, such as strength, stiffness and ductility values and overstrength of dowel-type connections with internal steel plates. A comprehensive literature review on experimental results on the evaluation of ductility on dowel-type steel-to-timber connections with slotted-in steel plates can be found in [17].

In the Background Document of the Chapter related to the specific rules for timber structures of the first release of Eurocode 8 [23], Ceccotti and Larsen presented moment-rotation diagrams of moment-resisting joints made with dowel-type fasteners with a very well pronounced rotational ductility and values of rotational ductility of 6 and even more, based on a study conducted by Ceccotti and Vignoli [24]. However, it should be remarked that there's a great difference in terms of values between rotational and displacement ductility; in case of moment-resisting joints, values of 10 and even more of rotational ductility are not so hard to be reached, whereas for displacement ductility values of more than 4 are very hard to be reached. Upon these studies, and other studies about the cyclic behaviour of bolted

Fig. 8. Specimen split along the slot line (bracket - type opening) after the monotonic test.

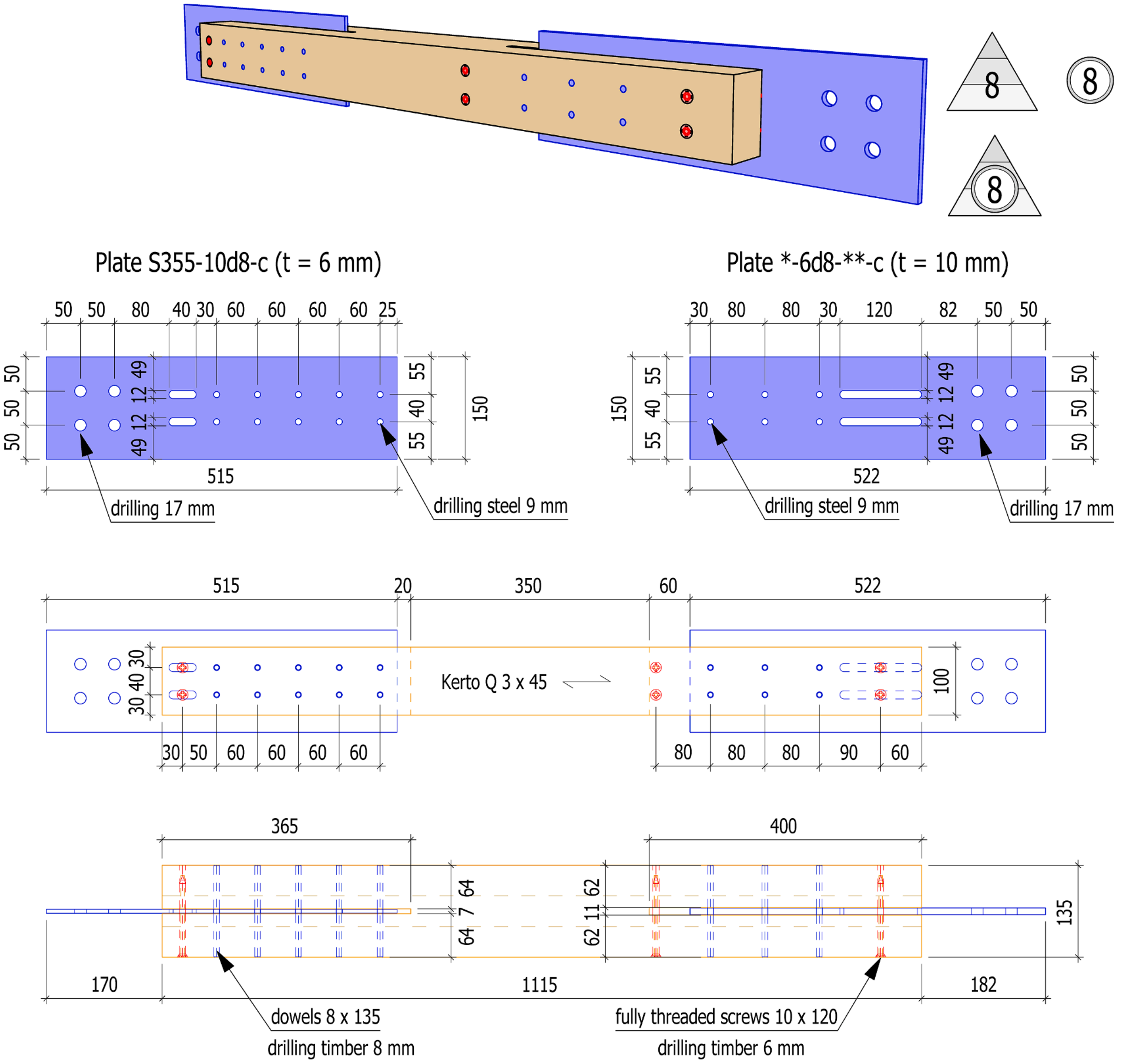


Fig. 9. Layout of specimens 2S-6d8-**-c (LVL-C with confinement screws on both sides of the dowel group = full confinement, fixing connection on the left, tested connection with different notch effect restraining measures on the right).

Table 1
Designation, details of the notch effect restraining measures (K = Hierarchy of the strengths according to equation (1); R = Rounding of the plate hole edges according to equation (2) (r = 2 mm)), steel grades and their post-elastic properties for the 12 specimens (triplicates).

Test	Series	Plate	Dowels	k_s [–]	A_{gt} [%]	k_f [–]	Rounding
Monotonic	2S-6d8-RK-m	DD11	A-ETG100	1.33	13.1	0.73	r = 2 mm
Cyclic	2S-6d8-K-c	DD11	A-ETG100	1.33	13.1	0.73	none
	2S-6d8-R-c	S355	S235JR	1.21	17.9	1.18	r = 2 mm
	2S-6d8-RK-c	DD11	A-ETG100	1.33	13.1	0.73	r = 2 mm

Where k_f indicates the ratio between the ultimate tensile strength of the plate and the yield strength of the dowel:

$k_f = f_{u,plate}/f_{y,dowel}$ (3)

connections [25] and sheathing-to-framing connections in Light-frame walls [26], were based the ductility provisions for dissipative zones in Medium and High Ductility Class which are still included in the current version of Chapter 8 of Eurocode 8 [1].

Ceccotti et al. [27] presented results of tests on glulam 12 mm diameter dowelled connections with slotted in steel plates where displacement ductility values of 4 were reached. However, it should be remarked that the joint configuration presented an over-design of the glulam elements with respect to the joint strength. Interestingly, these tests were performed using a joint confinement made with 16 mm diameter steel bolts.

Follesa et al. [28] tested different types of vertical joints in cross-laminated timber walls with different types of fasteners comparing them in terms of strength and stiffness. Gavric et al. [29] found very high values of cyclic ductility in parallel and orthogonal panel-to-panel CLT connections made with self-tapping screws, with values ranging from 5 to even 23, however no slotted-in steel plates were used in the joint configuration.

Dorn et al. [30] tested 64 steel-to-timber dowel-type connections loaded parallel to the fiber direction investigating the effect of the effects

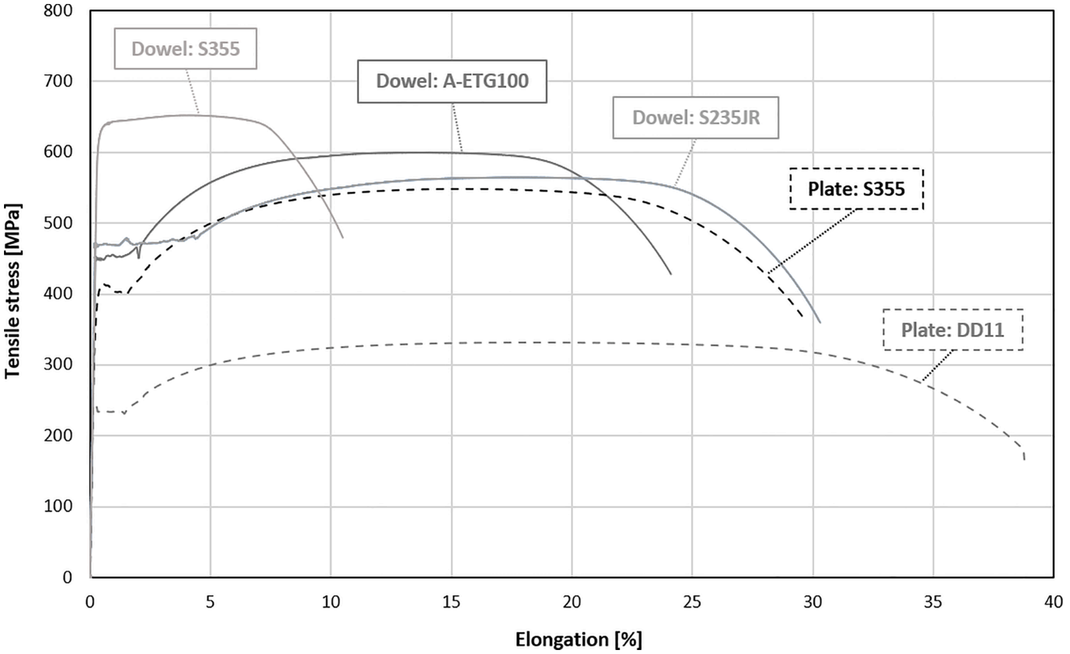


Fig. 10. Stress-elongation diagrams of the steel used for the dowels and for the plates.

Table 2
Specimen ID, steel designation properties of the dowels and number of specimens.

Specimen ID resp. steel designation	Properties of the dowel steel				Number of specimens	
	A_{gt} [%]	k_s [-]	f_y [MPa]	f_u [MPa]	Monotonic	Cyclic
S355	3.4	1.06	706	750	3	3
Annealed ETG100	11.1	1.26	522	657	3	3
Annealed S355	15.2	1.48	315	466	3	3
S235JR	20.5	1.24	425	526	3	3

Table 3
Yield displacement values used for the control of the cyclic tests.

Specimen	$V_{y,m}$
Notch effect restraining measures	2.4 mm
Rounding and hierarchy	1.8 mm
Steel quality	1.55 mm

of dowel roughness and lateral reinforcement on the connection ductility. The specimen tested with increased dowel roughness showed an increase of both, ultimate load and ductility. Ottenhaus et al. [9] tested different connection layouts for CLT dowelled connections, making use of mild steel dowels and internal steel plates, under monotonic and cyclic loading to evaluate theoretically determined overstrength values and study the influence of cyclic loading on overstrength. High values of ductility were reached, even for cyclic testing. Smith et al [31] proposed a ductility classification based on a proposed definition of characteristic yield and ultimate deformations. Finally, Brown and Li [32] presented an interesting experimental study to assess the structural performance of dowelled cross-laminated timber (CLT) hold-down connections with increased end distances and row spacing and also in some cases screw reinforcement, which proved to be effective measures in order to increase the connection performance in terms of strength and ductility.

As for code requirements contained in international codes there are currently no specifications concerning the notch effect. As reported in Ottenhaus et al. [33] an allowable range for f_y and f_y/f_u ratio is given in AS/NZS 4671. Only some basic specifications can be found in UNI EN 1993–1–1 (Eurocode 3: Design of steel structures - Part 1–1: General rules and rules for buildings) [34] concerning countersunk holes for joints made with countersunk head screws.

3. Material and methods

In the following paragraphs three main questions will be answered consecutively:

1) Does restraining the notch effect on steel dowels improve the ductility?
2) Which notch effect restraining measure improves the ductility most?
3) Which kind of steel improves the ductility of notch effect restrained connections most?

This approach is shown schematically in Fig. 4

4. Specimens

4.1. Specimens for the preliminary check of notch effect restraining methods

The specimens were made of Laminated Veneer Lumber (LVL-C) made of cross-bonded layers (Kerto-Q from Metsäwood [35]) with a cross section of 100 × 180 mm^2. The tested connection was made of two slotted-in steel plates inserted and fastened with 9 steel dowels with a diameter of 6.0 mm. This leads to a slenderness of the dowels of 8.9 (53.5 mm / 6 mm) The timber section was designed with sufficient overstrength ($\gamma_{Rd} \geq 1.6$) in accordance with the recommendation from [5]. These specimens fully correspond to those of the Beta 2 (LVL with confinement) series presented in [17]. As there were enough unused dowels left over from those previous tests for the specimen ID B.5 (steel grade Annealed ETG 100 with $f_y = 512$ MPa, $f_u = 627$ MPa, ks = 1,23, Agt = 12,2%), dowels with exactly the same properties could be used, making it possible to primarily observe the action of the notch effect restraining measures. In comparison with the specimen B.5 previously tested, only three points were modified:

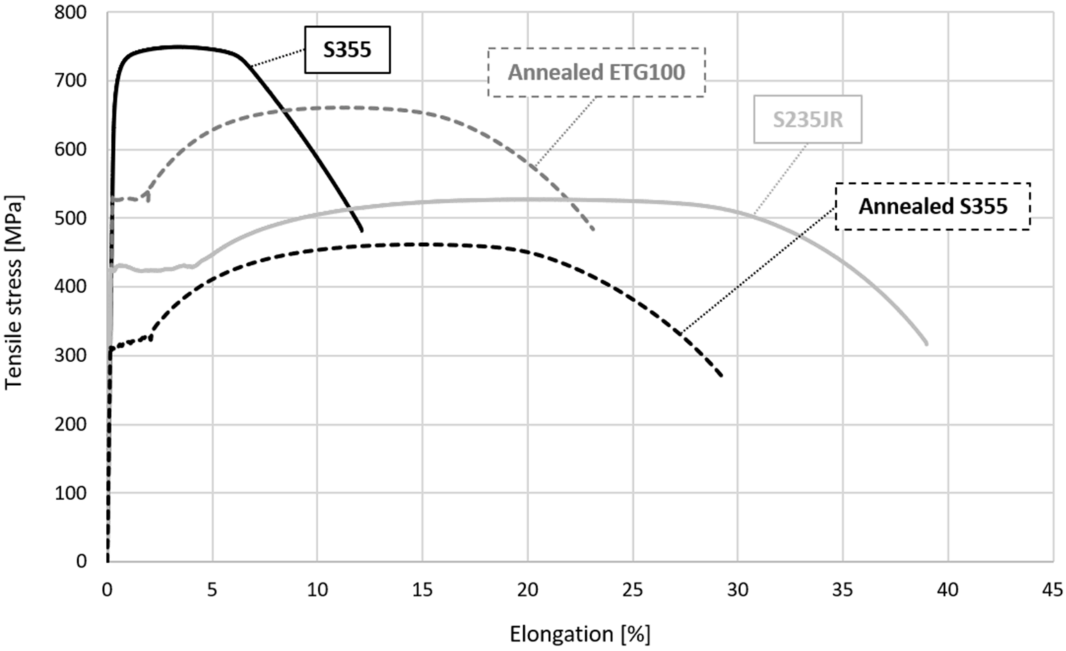


Fig. 11. Stress-elongation diagrams of the steel used for the dowels.

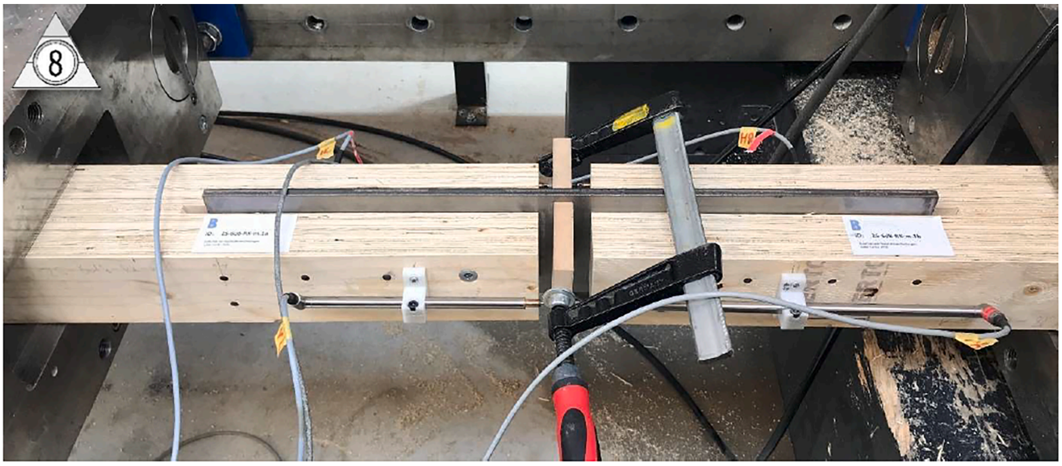


Fig. 12. Test setup of the monotonic tension tests.

1) thickness of the steel plates 10 mm instead of 5 mm
2) steel grade of the steel plates DD11 instead of S355
3) plate hole edges rounded with r = 2 mm

The thickness of the steel plate may have an influence on ductility. Investigations about the influence of the plate thickness on the connection stiffness at the elastic range of the connection were performed in [36]. However, in this case it is assumed that the influence of the plate thickness on the connection ductility is negligible.

Fig. 5 shows the details of the used specimens. Three replicates have been tested.

The setup has been chosen to fulfil both requirements proposed by [17] expressed on Equations (1) and (2).

The steel plate shows an ultimate tensile strength of $f_u = 331$ MPa, the dowel a yield strength of $f_y = 512$ MPa. Thus, the proposed requirement for the hierarchy of the strength is with $f_{u,plate} = 0.65\ f_{y,dowel}$ largely fulfilled. Steel was tested according to EN10002-1 [36] and using a testing machine Zwick 200 kN. Fig. 6 shows the stress-elongation diagrams of the steel plate and of the dowel.

4.2. Specimens for rounding and hierarchy

According to Eurocode 5 [14], for dowelled connections the dowel diameter should be greater than 6 mm and less than 30 mm. Furthermore, the investigations were improved with a different configuration. For these reasons, the dowel diameter was increased at 8 mm and the number of steel plates reduced to one, leading to a dowel slenderness of 7.8 (62 mm / 8 mm). This further configuration was introduced with the aim of eliminating potential middle part brittle failures of the timber member. All specimens were made of Laminated Veneer Lumber (LVL-C) made of cross-bonded layers (Kerto-Q from Metsäwood [35]) with a cross section of 100 × 135 mm^2. The slotted-in steel plate had a thickness of 10 mm and is fastened with 6 steel dowels with a diameter of 8.0 mm. According to the recommendation given in [5] the timber section was designed with an overstrength $\gamma_{Rd} \geq 1.6$.

Fig. 7 shows the specimens for monotonic test and Fig. 9 the specimens for the cyclic test.

Since timber members split up during the monotonic test (Fig. 8), fully threaded screws have been added at the bottom of the slot (see

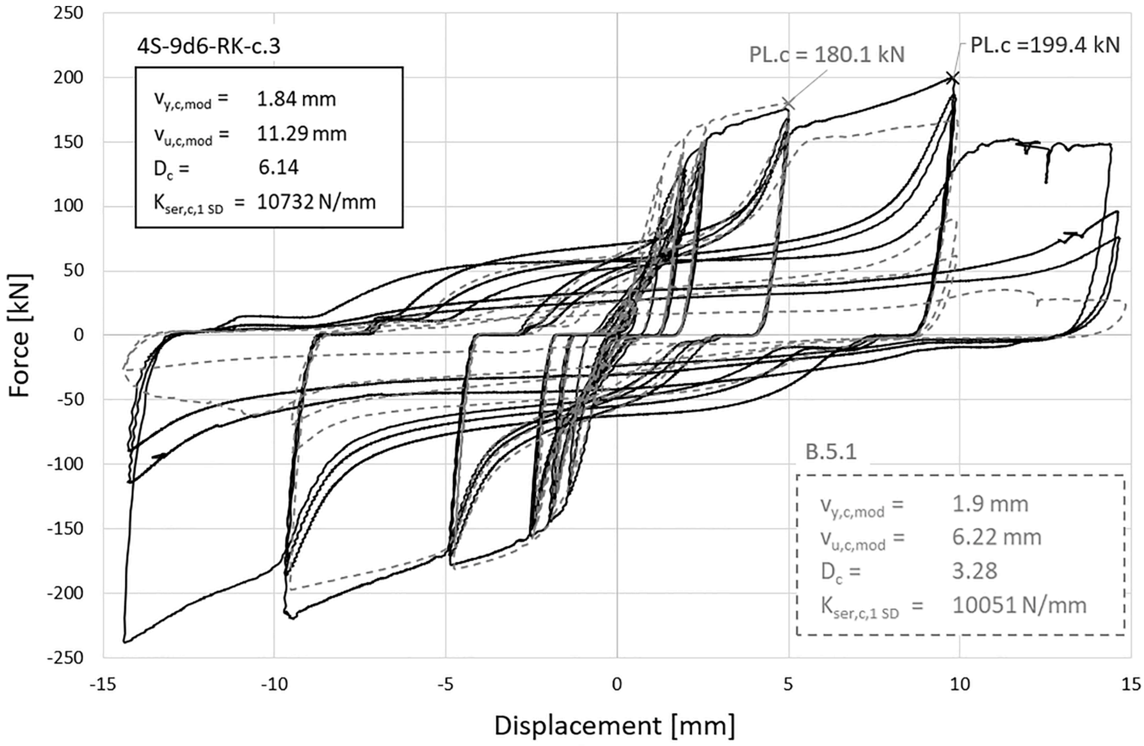


Fig. 13. Comparison of a connection without notch effect restraining measures (specimen B.5.1 according to [17]) and the same connection including notch effect restraining measures.

Fig. 14. Specimen 4S-9d6-RK-c.2 – Left: Timber members and steel plates - Right on the top: Dowels (failure mode 3) – Right on the bottom: Holes with crushed rounded edges. (The symbol left on the top means that both notch effect restraining measures have been taken).

Fig. 9) to prevent any timber member failure during the cyclic test. Using LVL-C and adding screws on both sides of the dowel group, the timber member is qualified as “fully confined”.

Specimens were designed to find out which measures are suitable to restrain the notch effect. The test plan is given in Table 1. One specimen type for the cyclic test fulfil only the hierarchy of the strength (equation (1), 2S-6d8-K-c), another has only rounded hole edges (equation (2), 2S-6d8-R-c) with r = 2 mm and the last one as well as that for the monotonic test combined both measures (2S-6d8RK-c and 2S-6d8-RK-m. Steel was tested according to EN10002-1 [37] and using a testing machine Zwick 200 kN. Fig. 10 shows the stress-elongation diagrams of the implemented steel both for dowels and plates.

4.3. Specimens for steel quality

All 24 tested specimens were made of Laminated Veneer Lumber (LVL-C) made of cross-bonded layers (Kerto-Q from Metsäwood [35]) with a cross section of 100 × 135 mm^2. The slotted-in steel plate S355 has a thickness of 10 mm and is fastened with 6 steel dowels with a diameter of 8.0 mm. This leads to a slenderness of the dowels of 7.8 (62 mm / 8 mm). The edges of the plate holes were rounded with r = 2 mm and again the timber section was designed with an overstrength factor

Table 4
Ductility of the 6 specimens (triplicates) of the cyclic test evaluated according to the current EN 12,512 [38] and to the revision proposal 2020 [39].

Timber member	Notch effect restraining measures	Specimen ID	Ductility grade Number of specimens that have fulfilled the requirements of EN12512 out of the 3 tested specimens			Ductility index according to the revision proposal
			$\mathbf{V_y}$	$\mathbf{2\ V_y}$	$\mathbf{4\ V_y}$	$\mathbf{D_c}$
LVL confined as described in [17]	none	B.5	3	3 $\mathbf{D_{c,EN} = 2}$	0	3.3; 3.4; 4.2 Average: $\mathbf{D_{c,Prop} = 3.6}$
LVL confined	Hierarchy and rounding (RK)	4S-9d6-RK	3	3	3 $\mathbf{D_{c,EN} = 4}$	5.2; 5.3; 6.1 Average $\mathbf{D_{c,Prop} = 5.6}$

Table 5
Results of the monotonic test in terms of ductility, stiffness, and peak load.

2S-6d8 Configuration	Specimen-ID	D_m [-]	$K_{ser.m.1SD}$ [N/mm]	$P_{L.m}$ [kN]
	2S-6d8-RK-m.1a	≥ 13.8	10,151	128.7
	2S-6d8-RK-m.1b	28.8	10,066	
	2S-6d8-RK-m.2a	29.2	10,284	126.4
$k_s = 1.33$	2S-6d8-RK-m.2b	≥ 13.9	10,795	
$A_{gt} = 13.1\%$	2S-6d8-RK-m.3a	≥ 13.8	10,871	123.9
$k_f = 0.73$	2S-6d8-RK-m.3b[1]	16.8	8,172	
	Mean	29.0	10,433	126.3

[1] This connection is considered as an outlier and is therefore not taken into account in the calculation of the mean value. The curve of the evaluation diagram indicates that the test specimen slipped slightly out of one of the clamping devices during the test. However, there is no certainty about the reason for the deviations.

$\gamma_{Rd} \geq 1.6$, in accordance with the recommendation from [6]. 12 specimens were subjected to monotonic test and the other 12 to cyclic test. The specimens for the monotonic tests are showed in Fig. 7, with an exception: they are fully confined, which means that fully threaded screws have also been inserted at the slot bottom. This full confinement should prevent any timber failure. The specimens for the cyclic tests correspond exactly to those showed in Fig. 9. The specimens intended for the monotonic and cyclic tests were different because different testing machines were used. Apart from this difference linked to the configuration of the test, all specimens were strictly identical with only one difference: the steel grade of the dowels. For this reason, the specimen ID given in Table 2 corresponds simply to the steel grade of the dowels. The steel used for the specimens has been selected respectively annealed to provide a wide range of elongation at maximum tensile stress A_{gt} and strain hardening ratio k_s. All dowel samples had a diameter of 8 mm and a length of 135 mm. Six specimens per steel grade were tested according to EN10002-1 [37] and using a testing machine Zwick 200 kN. Table 2 shows that the mean values obtained by testing once more strongly overpass the code requirements (S355 with fu = 750 MPa ≫ 470 MPa respectively S235 with fu = 526 MPa ≫ 360 MPa) according to EN10025-2 [41]. Fig. 11 shows the stress-elongation diagrams of the dowels.

5. Test method and evaluation

5.1. Monotonic tests

Tests were carried out according to EN 26891:1991 [40]. A horizontal machine “GEZU” for tensile strength testing with a maximal capacity of 850 kN was used. “TextXpert II from Zwick GmbH was used as testing software. Based on similar tests, the ultimate tensile force was estimated at about 130 kN (Fig. 12). The specimens of section § 3.1.1 were mainly tested to evaluate the yield displacement v_y which is required for the planned cyclic tests. The specimens of section § 3.1.3 were in addition to the yield displacement v_y conducted to assess the serial yielding.

5.1.1. Cyclic tests

Cyclic tests were carried out according to EN 12512 [38] using testing frame controlled by the testing software DION 7 from Walter + Bai. The testing frame has a maximal capacity of 1000 kN both in tension and compression. The test was displacement controlled according to EN 12512 [38]. The initial value was the yield displacement $V_{y,m}$ determined on the basis of the monotonic test series.

In order to obtain comparable results, the cyclic tests were conducted using the same yield displacement per type of specimen. For the specimens of paragraph 3.1.1 the same displacement as in [17] § 3.2.2.2 was used. The yield displacement for the specimens of paragraph 3.1.2 and 3.1.3 correspond to the mean value obtained by the monotonic test. All yield displacements were given in Evaluation (Table 3).

5.1.2. Monotonic tests

V_y was determined according to EN12512 [38]. However, as the connections have different initial slip, this slip was subtracted from the yield displacement $V_{y,m}$ and from the ultimate displacement $V_{u,m}$ (index

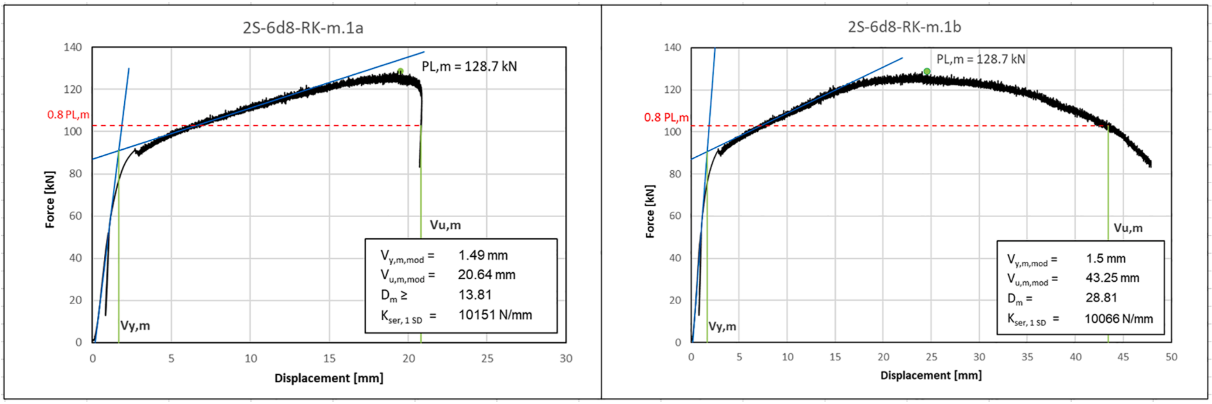
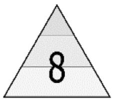


Fig. 15. Force-displacement diagrams of both connections of the specimen 2S-6d8-RK-m.1.

Fig. 16. Plastically deformed dowel, rounded and crushed plate hole edges after the monotonic test, both pictures from the specimen 2S-6d8-RK-m.1b (see Fig. 15 Force-displacement diagrams of both connections of the specimen 2S-6d8-RK-m.1).

Table 6
Results of the monotonic test in terms of ductility, stiffness, and peak load.

Configuration	Steel properties	ID	$D_{c,Prop}$ [-]	$K_{ser.c.1SD}$ [N/mm]	$P_{L.c}$ [kN]
	$f_y = 451$ N/mm^2 $f_u = 599$ N/mm^2 $k_s = 1.33$ $A_{gt} = 13.1\%$ $k_f = 0.73$	1	2.7	5,486	102.4
		2	4.4	8,975	107.3
		3	4.1	8,881	105.0
2S-6d8-K-c.		Mean	4.3	8,928	106.1
	$f_y = 465$ N/mm^2 $f_u = 564$ N/mm^2 $k_s = 1.21$ $A_{gt} = 17.9$ % $k_f = 1.18$	1	5.5	7,682	111.5
		2	7.3	10,078	112.5
		3	6.8	9,346	109.8
2S-6d8-R-c.		Mean	7.1	9,712	111.3
	$f_y = 451$ N/mm^2 $f_u = 599$ N/mm^2 $k_s = 1.33$ $A_{gt} = 13.1\%$ $k_f = 0.73$	1	4.8	10,028	105.4
		2	4.4	9,301	109.5
		3	4.3	8,858	107.0
2S-6d8-RK-c.		Mean	4.5	9,396	107.3

“m” for monotonic to distinguish it from the cyclic test results marked with the index “c”). The ductility from the monotonic tests was determined according to Eq. (4).

$$D_m = \frac{V_{u,m,mod}}{V_{y,m,mod}} \tag{4}$$

For the specimens of paragraph 3.1.3 the sum of the ultimate displacements of both symmetrical connections was divided the by the sum of their yield displacements. Already used in [17] this value was named $D_{a+b,m}$ and describes the ductility of two serially arranged connections Eq. (5).

$$D_{a+b,m} = \frac{V_{u,m,mod,a} + V_{u,m,mod,b}}{V_{y,m,mod,a} + V_{y,m,mod,b}} \tag{5}$$

A further value evaluated was the peak load displacement $V_{PL.m}$.

5.1.3. Cyclic tests

As explained in [17] in a first step, the evaluation was carried out strictly according to the current version of EN12512 [38]. However, as this test standard and Eurocode 8 are currently under revision, in a second stage the evaluation was done according to the proposal of revisions of both standards referenced in [5], [6] and [39]. In order to get results according to the standard *currently* in force, the test method used was that of the current standard. After the tests, the evaluation method described in the revision proposal of EN 12,512 [39] was used. The reason behind this choice was to obtain a better comparison of the series. The revision proposal gives a way to get ductility values with decimals, which is not possible according to the current version which merely indicates whether a ductility of 1, 2, 4, 6 etc. can be reached or not.

To make the results easier to be understood, the values from the evaluation according to EN12512 [38] are called ductility grade ($D_{c,EN}$, e.g. 2, 4, 6) and those from the revision proposal [39], ductility index ($D_{c,Prop}$ e.g. 3.6, 5.6, 7.1). In the proposal for the revision of EN 12512 [39] the ultimate displacement of the cyclic test, $V_{u,c}$ is defined as the minimum value between the displacements in a cyclic curve corresponding to:

i. failure.
ii. the displacement related to 80 % of the peak load $P_{L,c}$ evaluated on the first load envelope curve after the peak load.
iii. the displacement characterized by a strength degradation factor $k_{deg}(v)$ equal to or lower than $k_{deg,min}$, whichever occurs first. The value of non-dimensional coefficient $k_{deg,min}$ is set on 0.75 in accordance with the current draft of the revision of Eurocode 8 [5]. The value of $k_{deg}(v)$ is equal to the ratio between the value from the third load envelope curve and the first load envelope curve at the point v.

The ductility obtained through the cyclic test is defined by Eq. (6):

$$D_c = \frac{V_{u,c}}{V_{y,c}} \tag{6}$$

6. Results and discussion

6.1. Check of notch effect restraining measures

Fig. 13 compares the connection behaviour under cyclic loading according to EN 12512 [38] and evaluated according to [39] of a connection without notch effect restraining measures (specimen B.5.1 according to [17] and the same connection including the notch effect restraining measures, hierarchy of the strengths and rounding of the steel hole edges. As it can be observed the proposed detailing measures led to a significant increase of the energy dissipation capacity of the connection.Fig. 14

Table 4 gives the test results. The notch effect restraining measures allow to double the connection ductility according to EN 12512 [38]. Evaluated according to the revision proposal [39], the ductility increases from 3.6 to 5.6. As the yield displacement is similar and the ultimate displacement increases as well, the ductility evaluation issues [42,43] are not problematic in this case. Without notch effect restraining measures and implemented in glulam without confinement, the same connection reaches a ductility of 2.7 (compare [17] § 4.2.2, mean value of the specimens B.1, B.2 and B.3, 9 specimens in total). Timber member

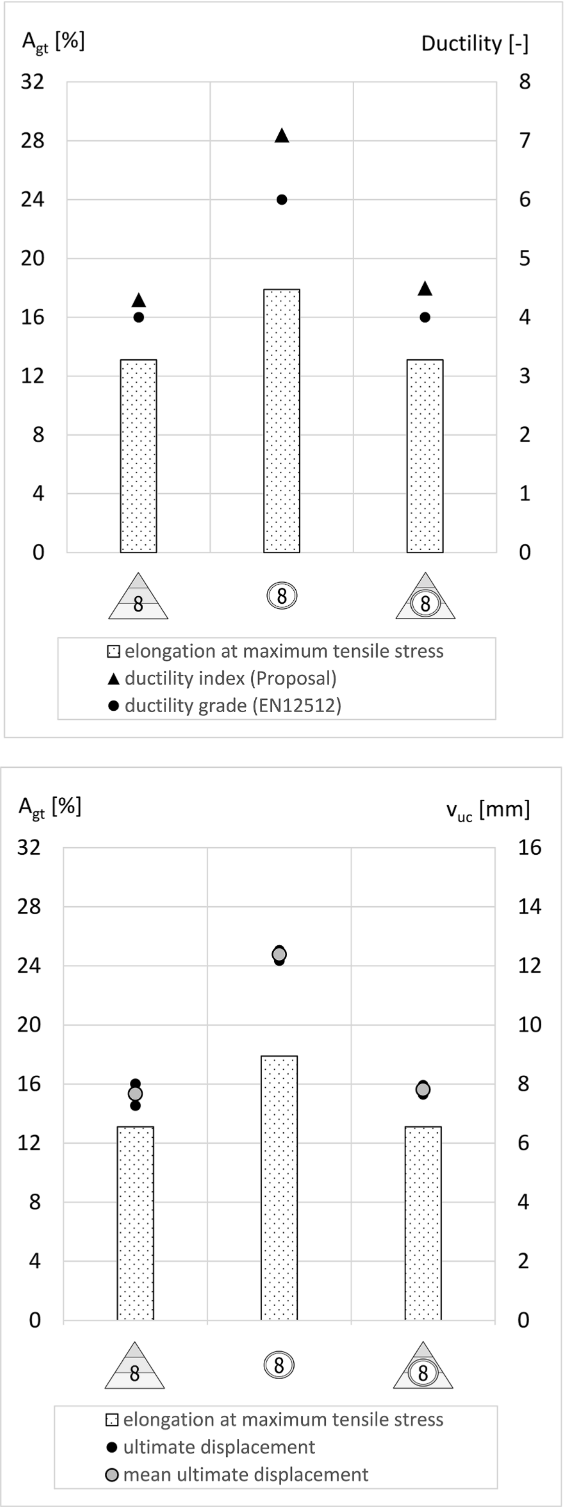


Fig. 17. Ductility grade and ductility index in the top, ultimate displacement in the lower figure, elongation at maximum tensile stress A_{gt} of the implemented dowels for different notch-effect restraining measures.

confinement combined with notch effect restraining measures and a chosen steel quality allowed to significantly increase the ductility. This is mainly due to the connection carrying higher forces at a higher displacement.

However, after reversing the cycle these connections have a certain amount of "play" shown by a long displacement until the stiffness increases significantly (Fig. 13). This characteristic is referred to as pinching [44]. Pinching of connections can lead to disadvantageous structural behaviour due to high accelerations even if sufficient ductility is provided.

7. Rounding and hierarchy of strengths

7.1. Monotonic tests

Table 5 gives an overview of the results from the monotonic tests. Fig. 15 shows that both connections yielded together until the peak load of the weaker connection was reached. After that point, only the weaker connection continued to yield. The hole edges were crushed where expected according to the hierarchy of the yield strengths. This is clearly shown in Fig. 16.

7.1.1. Cyclic tests

Table 6 gives an overview of the results from the cyclic tests. Because of problems aroused during the tests (stability of the force - applying cylinder head and unplanned preloading), two specimens must be qualified as outliers and are crossed out. Fig. 17 compares graphically the ductility obtained by the different configurations.

The test specimens with only rounded hole edges as notch effect restraining measure showed the best results. By rounding the hole edges and using dowel steel with an elongation at maximum tensile stress A_{gt} of almost 18%, a ductility grade [38] of 6 and a ductility index [39] of 7.1 could be achieved. As the ultimate displacement increases similarly to the ductility, the evaluation issues [42,43] are not problematic in this case. Such values were hardly reached before in steel to timber doweled connections for displacement ductility. The measure taken enabled the connection to exploit their plastic deformation capacity to a large extent. In fact, the ultimate displacement depends on the elongation at maximum tensile stress if the yield strength is constant. A comparison of configurations "K" (only hierarchy of the strengths) and "RK" (both measures) also showed that the combination of the two measures did not result in a significant improvement in cyclic ductility.

Moreover, since no brittle failures in the timber members occurred, it can be assumed that the full confinement worked correctly.

Fig. 19 shows that the hole edges of the specimens where a hierarchy of the strengths was implemented (columns 1 and 3) are clearly more crushed than those for which a stronger steel plate was used.

8. Steel properties

8.1. Monotonic tests

Figs. 16 to 20 show the results of the monotonic tension tests and allow the identification of relationships and tendencies. The results (Fig. 20 and Fig. 21) seem to confirm that ductility depends on the elongation at maximum tensile stress. The connection including the steel grade with the highest A_{gt} value (S235JR: $A_{gt} = 20.5\%$). showed the highest ductility. It must be noted that, according to the results of monotonic tests, common doweled connections usually reach ductility values D_m from 3 to 5 (compare [16;17]). Thus, values approaching 30 are extremely high and demonstrate the effectiveness of the measures taken.

The highest peak load displacements $v_{PL,a+b,m}$ (Fig. 22 Peak load displacement vPL,m and steel properties of the used dowels) were reached from the connections using dowels with highest strain hardening ratio (A-S355: $k_s = 1.48$).

Concerning stiffness, Fig. 23 shows the highest value for the connections with S235JR. It must be added with this regard, that the surface of the S235JR was quite rough and could have contributed to the increase of stiffness e.g. due to a momentary enhanced rope effect. Putting aside the results of the S235JR series, it can be observed that stiffness increases with the increase of steel strength. This effect has already been mentioned in [17] § 4.3 and could be due to local and early yielding of

Fig. 18. Individual parts of the specimen 2S-6d8-R-c.3 after the cyclic test.

Fig. 19. Plate hole edges after the cyclic test. A hole of each specimen is shown.

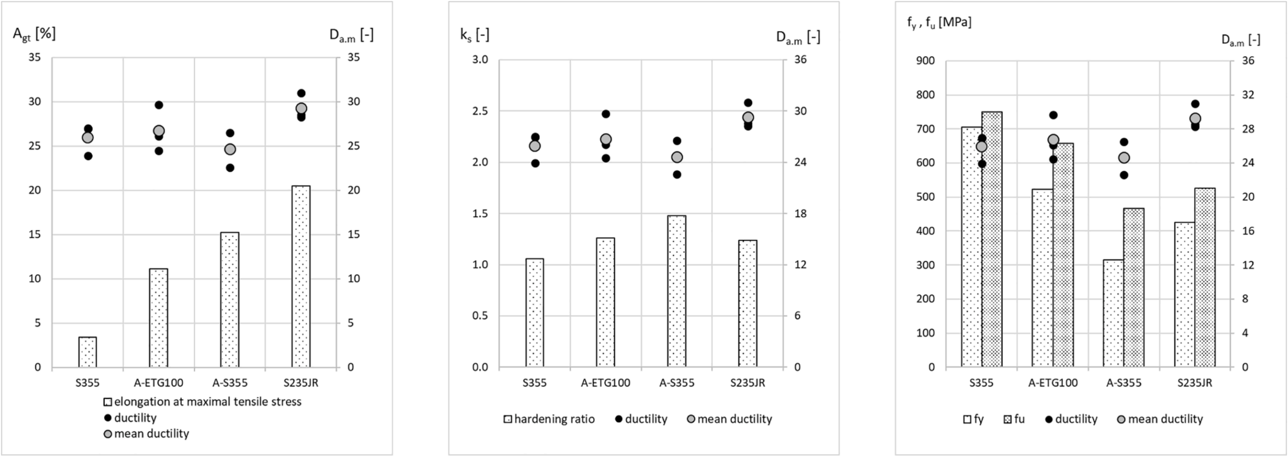


Fig. 20. Connection ductility $D_{a,m}$ and steel properties of the used dowels.

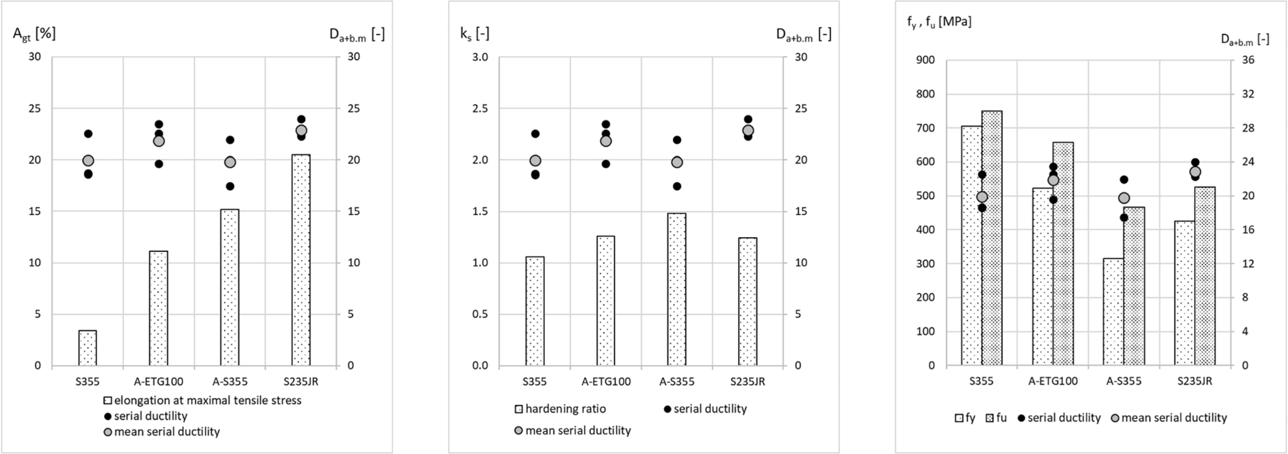


Fig. 21. Ductility $D_{a+b,m}$ of two serially arranged connections and steel properties of the used dowels.

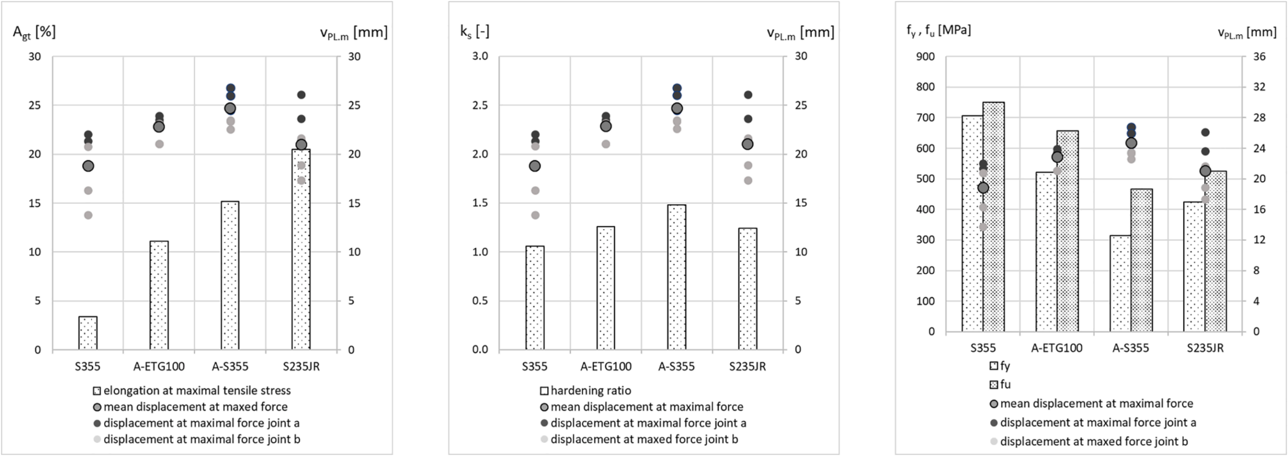


Fig. 22. Peak load displacement $v_{PL,m}$ and steel properties of the used dowels.

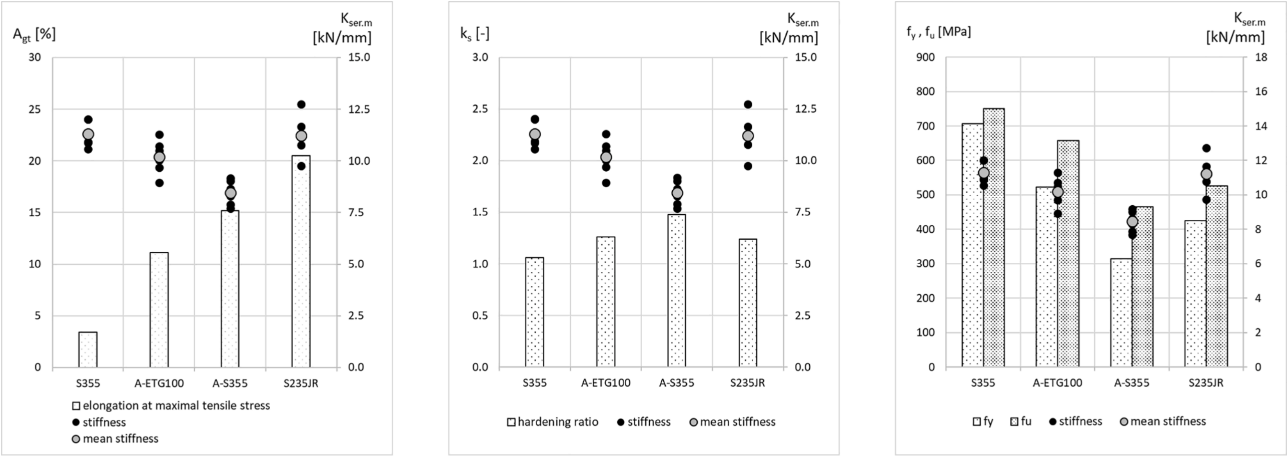


Fig. 23. Stiffness K_{ser} (converted for one dowel) and steel properties of the used dowels.

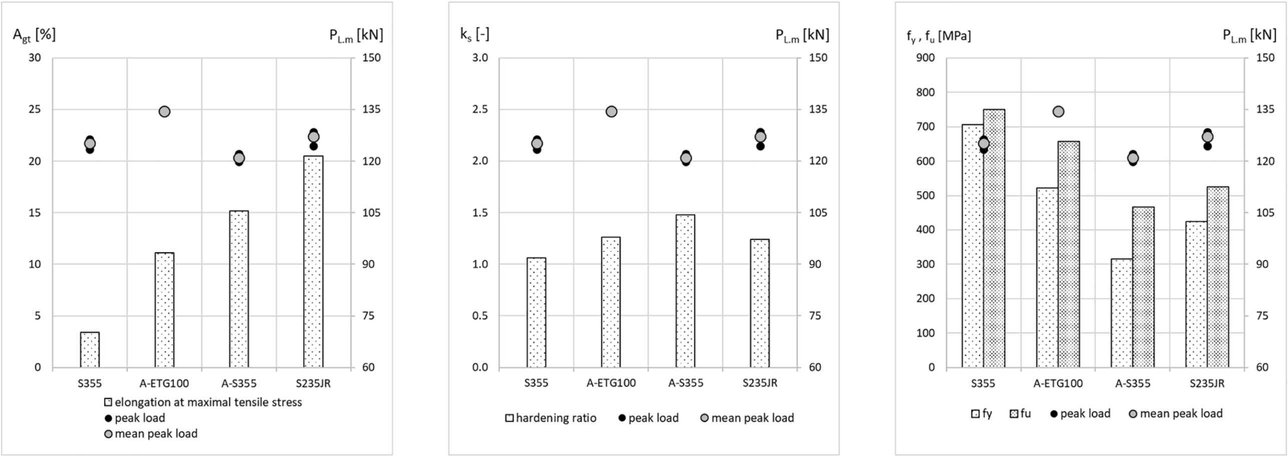


Fig. 24. Peak load $P_{L,m}$ of the timber connection and steel properties of the used dowels.

Fig. 25. Individual parts of the specimen with S235JR after the monotonic test.

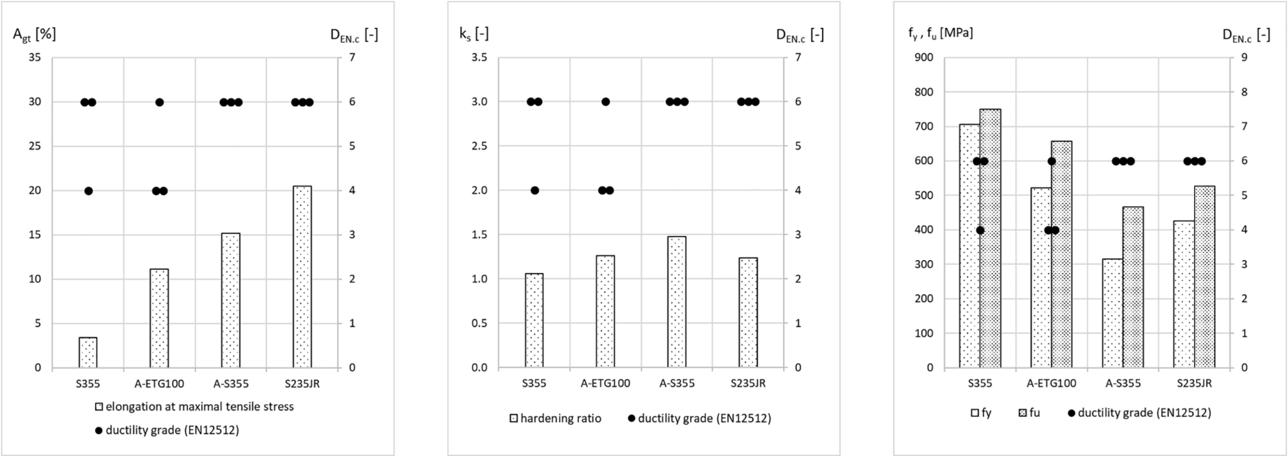


Fig. 26. Ductility grade $D_{c,EN}$ and steel properties of the used dowels.

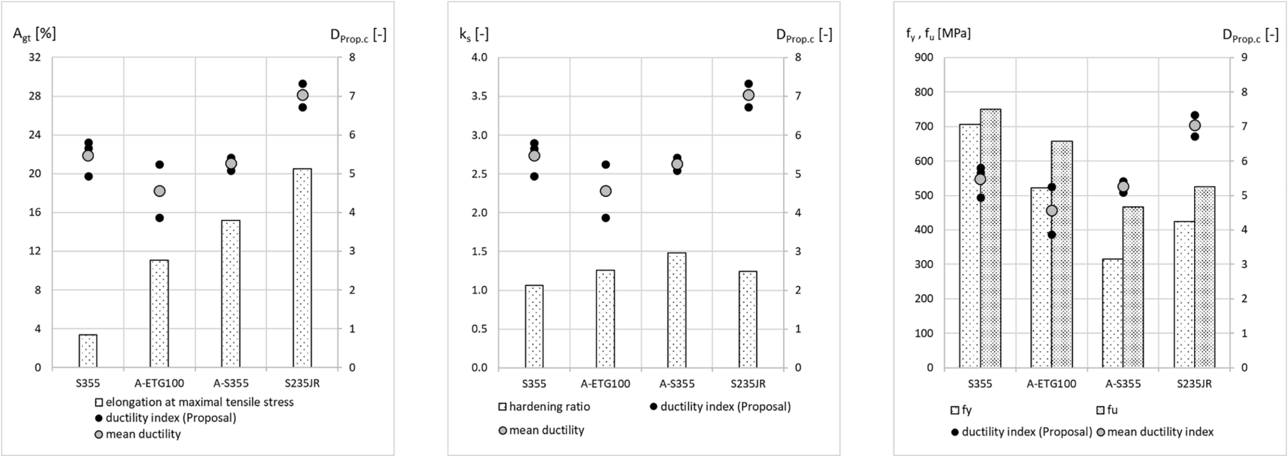


Fig. 27. Ductility index $D_{c,Prop}$ and steel properties of the used dowels.

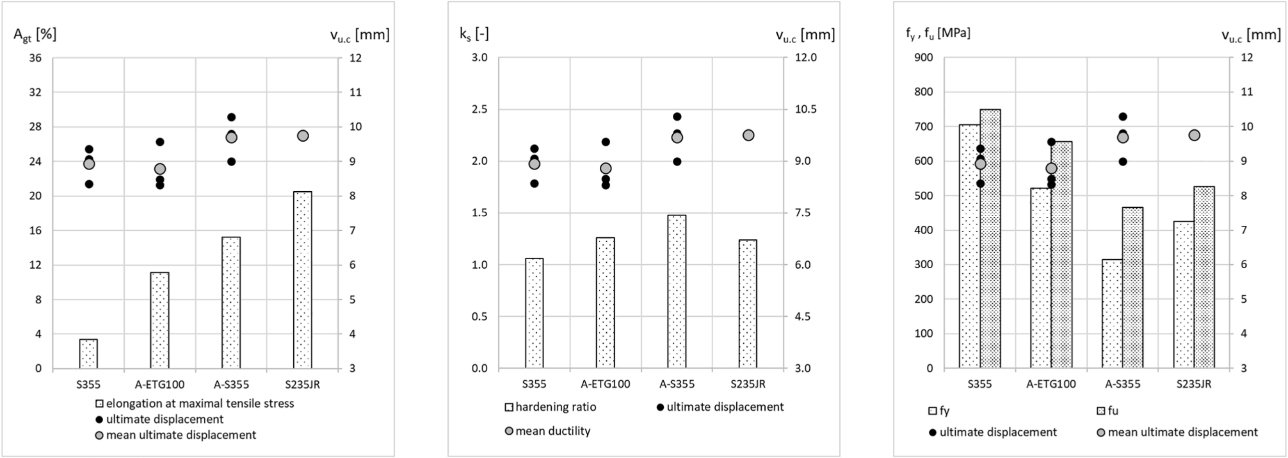


Fig. 28. Ultimate displacement $v_{u,c}$ and steel properties of the used dowels.

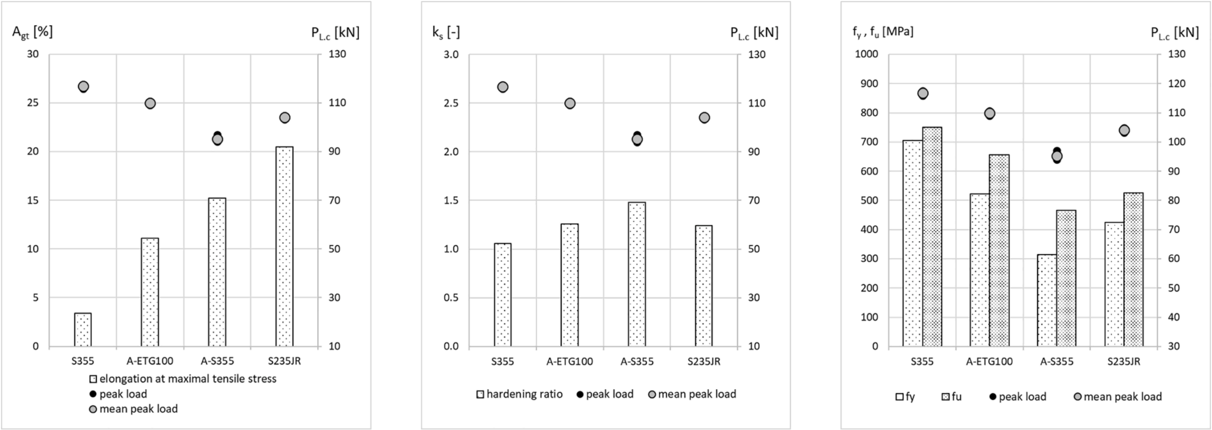


Fig. 29. Peak load $P_{L,c}$ of the timber connection and steel properties of the used dowels.

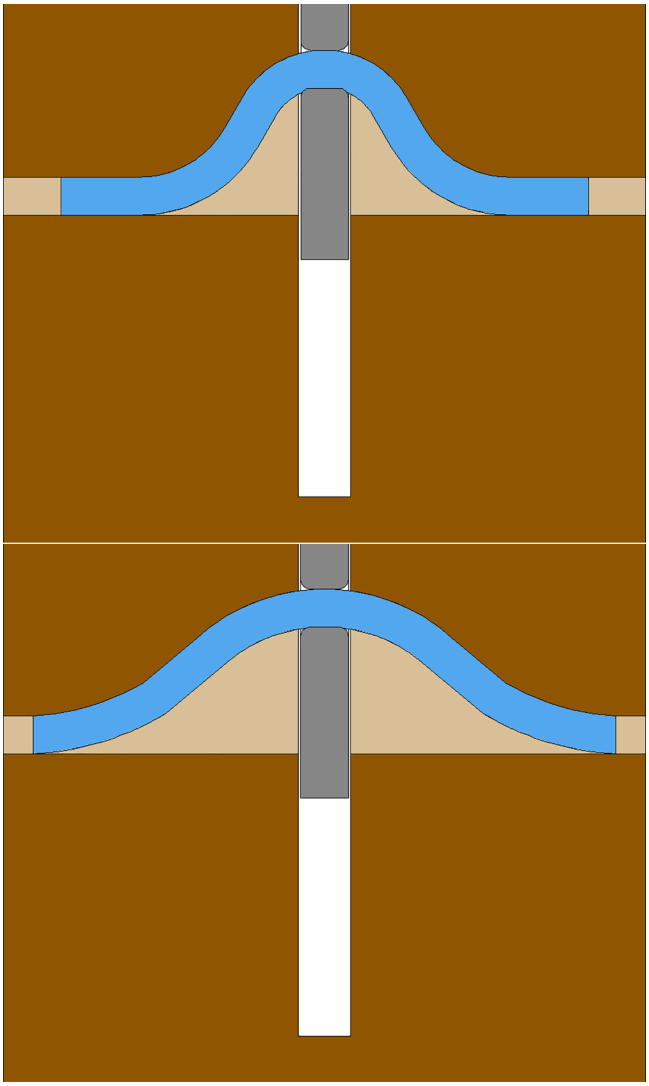


Fig. 30. Different dowel shapes at a given connection displacement. On the top high curvature at mode 3, bottom low curvature at mode 3.

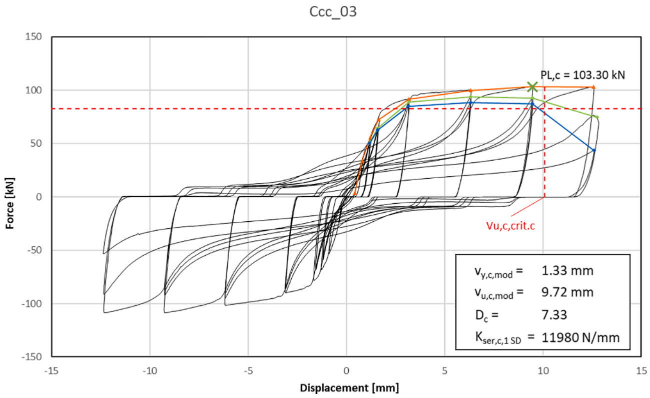


Fig. 31. Force-displacement diagram of one cyclic tested specimen with S235JR.

dowels within the so-called elastic area.

As seen in Fig. 24 the peak load doesn't strictly follow the steel strength. However, the weakest steel (A-S355: $f_y = 315$ MPa; $f_u = 466$ MPa) actually led to the lowest connection resistance. Interestingly, the connections including steel grades with favourable post-elastic properties (S235JR and A-ETG100) provided higher resistance than the connection with the strongest steel (S355) which also shows the poorest post-elastic characteristics.

8.1.1. *Cyclic tests*

Figs. 22 to 25 show the results of the cyclic tests and allow the identification of relationships and tendencies. The ductility index and the ultimate displacement $v_{u,c}$ of the connection with S-355 dowels is only about 5% lower than the one from the connection with S235JR dowels (Fig. 28). Therefore, the ductility index evaluation issues [42,43] are not problematic in this case. This is different from the results showed in § 4.2.2 and might be explained with i) the plastic hinge curvature differences shown in Fig. 30 and ii) constriction of the dowels as visible in Fig. 32. Due to the higher curvature, the dowels with a lower yield strength show a larger plasticization at the given connection displacement. The dowels were constricted in the contact area to the plate (Fig. 30). This constriction visibly correlates with the yield strength of the dowels (Table 2). Restricting the constriction of the dowels is not possible by capacity design because in failure mode 3 the contact surface is not clearly defined due to the curvature of the plastically deformed

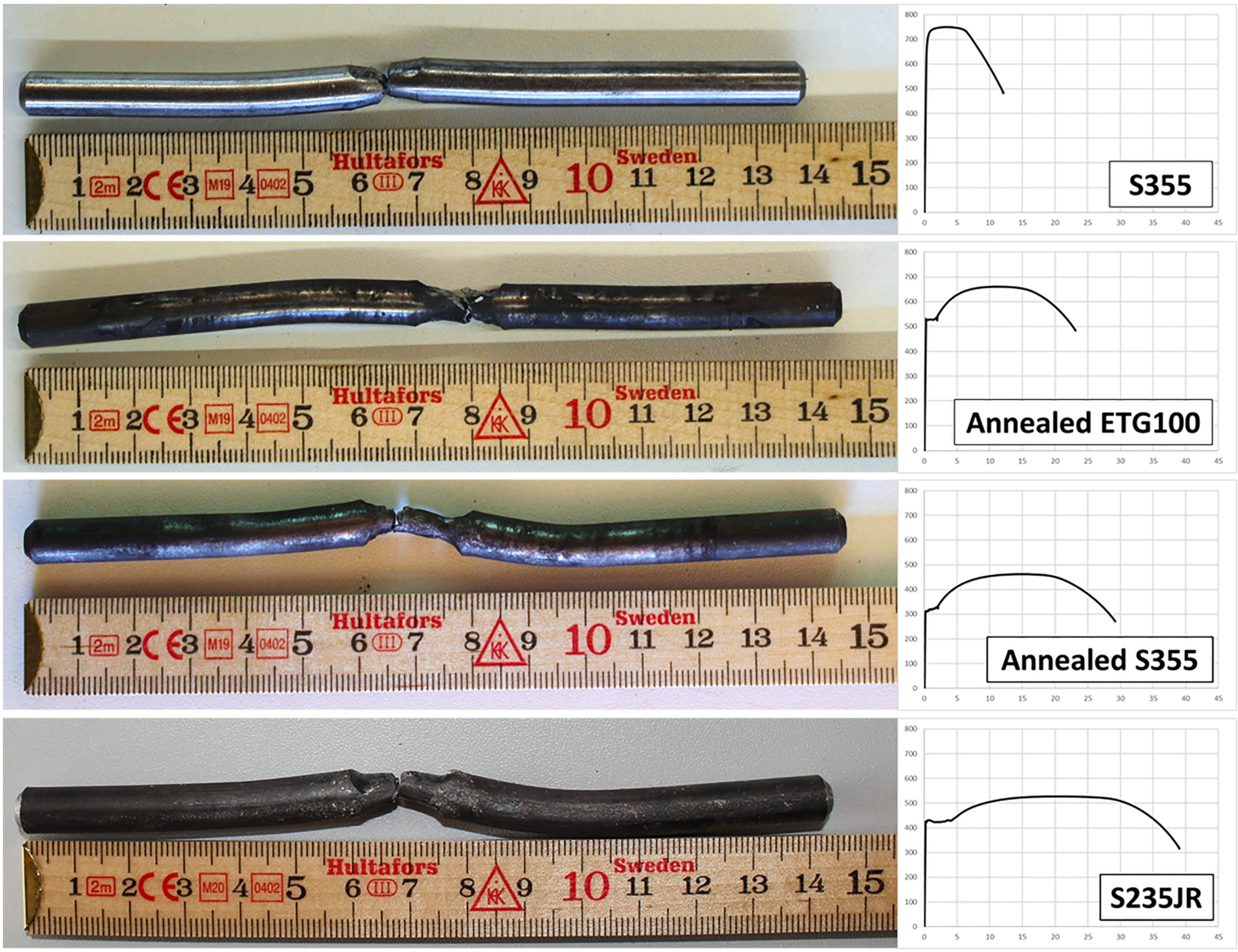


Fig. 32. Dowels of the different specimens after cyclic tests.

dowels. Therefore, an increase of the plate thickness does not allow to restrict constriction. Consequently, hierarchy between dowels and plate is needed. As from the monotonic tests, the results (Fig. 26 and Fig. 27) seem to confirm that ductility depends on the elongation at maximum tensile stress. Only the connections including the steel grades with the highest A_{gt} values (S235JR: A_{gt} = 20.5% and A-355: A_{gt} = 15.2%) reached the ductility grade $D_{c,EN}$ of 6 (required for DCH according to the current version of Eurocode 8 [1]) for all three specimens. Derived from cyclic test (which is decisive for earthquake design), a ductility grade of 4 (the minimum requirement for DCM according to [1]) was rarely measured before (compare [16,17] § 4.2.2) and often only 2 was reached. Thanks to the measures taken, ductility values of 6 ($D_{c,EN}$) or even 7,0 ($D_{c,Prop}$) are now possible. These values are very similar to those presented in section 4.2.2 ($D_{c,EN}$ = 6 and $D_{c,Prop}$ = 7.1) and confirm them.

Contrary to what was observed from the monotonic tests, the peak load $P_{L,c}$ follows clearly the steel strength (Fig. 29). This doesn't correspond to what previously observed [17] where is stated that "*For steel grades with equal steel strength, connections made with optimized dowels are about 1/3 stronger than those of common dowels*". An important distinction should be made with respect to this statement. Previously tested specimens were not "fully confined" so that even if limited, splitting and cracking of wood was nevertheless still possible at some extent. Thus a "softer" load introduction due to steel grades with favourable post-elastic properties could have led to a delay of the timber part failure and increased therefore the peak load, the timber member limiting the resistance. In fully confined members, failures of timber parts are no longer possible, and this effect seems to disappear.

Fig. 31 shows a force–displacement diagram of a specimen with S235JR. The specimen showed a value of cyclic ductility of 7.33, which results from the ratio between cyclic ultimate displacement and cyclic yield displacement. It should be noted that the ductility would reach almost the same values (7.42) if calculated using the monotonic yield displacement $v_{y,m}$, which was equal to 1.31 mm on average, instead of the cyclic yield displacement $v_{y,c}$.

9. Conclusions

The tests carried out with two slotted in plates showed that notch effect restraining measures, rounding and hierarchy of strengths, significantly increase the ductility of the doweled timber connection subjected to cyclic tests. The second series of tests have shown that both measures are effective in restraining the notch effect, and that simultaneous implementation of the two of them is not necessary. In the third series of tests constriction of the dowels occurred as the notch effect was restrained. Therefore, the full displacement capacity still could not be reached. If the following four measures are applied:

i. fully confined timber members,
ii. notch effect restraining measures,
iii. constriction restraining measures
iv. adequate steel grade with favourable post-elastic properties,

the connections can develop their full displacement capacity. Higher ductility rates allow more favourable values of the behaviour factor q and will therefore improve the energy dissipation of capacity designed timber structures.

Further investigation will be needed for the following aspects:

- The need for strength hierarchy between dowels and plate to restrain constriction of the dowels
- The interaction between slenderness, yield and ultimate strength of the dowels as well as embedment strength of the timber

Proper detailing including full confinement, constriction and notch-effect restraining measures should be carefully investigated and post-elastic steel properties no longer ignored.

Declaration of Competing Interest

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

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