MODE CROSS-OVER AND DUCTILITY OF DOWELLED LVL AND CLT CONNECTIONS UNDER MONOTONIC AND CYCLIC LOADING

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ABSTRACT: This paper presents an experimental study on dowelled connections in Cross-Laminated Timber (CLT) and Laminated Veneer Lumber (LVL) using ϕ20 mm mild steel dowels and internal steel plates. Connections designed to fail in brittle row shear and group tear-out were tested under monotonic loading to assess the validity of analytical models from literature and code provisions. Connections designed to provide non-linearity before failure and thus produce ductility were tested under both monotonic and cyclic loading to study the influence of cyclic loading on ductility and the possibility of mode cross-over. It was found that cross layers in CLT improve ductility. Furthermore, mode cross-over from ductile response to brittle failure was observed in both CLT and LVL connections. Nevertheless, a good amount of ductility was achieved in all layouts (except the LVL connections designed for group tear-out failure) before cross-over to brittle failure occurred.

KEYWORDS: Dowelled connections, Cross-laminated timber, Laminated veneer lumber, Ductility, Cyclic loading, mixed-mode failure, mode cross-over

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INTRODUCTION

Traditionally, in timber buildings, connections provide the main source of non-linearity and energy dissipation during a seismic event because timber itself is prone to brittle failure. Therefore, connection behaviour needs to be well understood to ensure seismic safety of timber buildings.

DUCTILITY

A building's ductile capacity is an important seismic design factor. Ductility is a measure of connection non-linearity and is commonly defined as $\mu = \Delta_u / \Delta_y$, where Δ_y is the yield displacement and Δ_u is the ultimate displacement, often defined as the post-peak displacement at 80% of the maximum load. Based on the assigned building ductility, the designer needs to detail specific connections with adequate ductility to achieve the desired reduction of seismic demand. This can be a challenging task, as it can be difficult to accurately predict the behaviour of connections under seismic loading. Furthermore, design codes often use ductility obtained from monotonic testing based on the assumption that similar ductile behaviour can be achieved under cyclic loading (Smith et al. 2015, Ottenhaus et al. 2016). In addition, it should be noted that different definitions of the yield point can lead to inconsistencies of ductility evaluations unless clearly defined in design codes (Jorissen and Fragiacomo 2011, Piazza et al. 2011, Flatscher 2016). For the purpose of this paper a connection which has a clearly defined yield point establishing non-linear behaviour is considered to be responding in a ductile manner.

MODE CROSS-OVER

Ductile and brittle behaviour of dowel-type connections have been extensively studied in literature (Jorissen and Fragiacomo 2011, Piazza et al. 2011, Quenneville and Morris 2009, Jensen and Quenneville 2011). Traditionally, ductile and brittle modes are treated as two separate responses. It is assumed that brittle failure can be avoided with adequate fastener spacing allowing the

connection to develop sufficient ductility. However, fastener embedment and associated timber densification underneath the fastener can reduce the effective shear plane length of the brittle modes and thereby decrease the connection's resistance against brittle failure (Novis et al. 2016, Zhang et al. 2016). A previously ductile responding connection can thus 'cross-over' to brittle failure which is referred to as mixed-mode response.

Fig. 1 shows the theoretical concept of cross-over: F_{BRu} refers to the connection's theoretical ultimate brittle resistance. For dowelled connections, F_{BRu} can be the ultimate row shear strength, F_{RSu}, the ultimate group tear-out strength, F_{GTu}, or the ultimate net tensile strength, F_{NTu}. The respective brittle failure modes are displayed in Fig. 2a. As F_{NTu} is not affected by dowel embedment it can be excluded in this illustration. F_{EYMu} denotes the connection's theoretical ultimate ductile capacity according to the European Yield Model (EYM) as shown Fig. 2b. F_{EYMy} is reached at the displacement Δ_y and is the connection's yield strength, F_y, regardless of the ultimate failure mode. F_u is the obtained ultimate strength at the displacement Δ_u. Note that F_u is defined as 80% F_{max}, however, if brittle failure occurs, F_u and F_{max} and the corresponding displacements are identical.

Fig. 1 shows the different possible connection responses which are defined by the connection's strength hierarchy:

a) Ductile: If $F_{BRu} >> F_{EYMu}$, the connection is able to respond in a fully ductile manner as $F_u = F_{EYMu}$

b) Ductile mixed-mode: If F_{BRu} is higher than F_{EYMu}, mode cross-over occurs before F_{EYMu} is reached: $F_u < F_{EYMu}$. However, the connection may still be able to achieve a high level of ductility depending on the initial difference between F_u and F_{EYMy} and accordingly the difference between Δ_u and Δ_y.

c) Nominally ductile mixed-mode: If the strength hierarchy of the connection is $F_{EYMy} < F_{BRu} < F_{EYMu}$, only a small amount of non-linear deformation can be achieved before mode cross-over occurs resulting in a connection with nominal ductility.

d) Brittle: If $F_{BRu} < F_{EYMy} < F_{EYMu}$, the connection will fail without any fastener yielding.

If the connection's ductile behaviour is well described and the expression for the reduced brittle strength, F_{BRred}, is known, it is possible to accurately predict Δ_u and the connection's ductility $\mu = \Delta_u / \Delta_y$ (Zhang et al. 2016, Novis et al. 2016), without conducting experimental testing.

The effect of cyclic loading on strength and ductility has been studied in literature (Mohammad et al. 1998, Yasumura 1998). As fastener embedment can only provide limited hysteretic energy release under cyclic loading, timber structures rely on fastener yielding for ductility during seismic events. However, this ductile response can be impaired by onset of brittle failure due to mode cross-over.

EXPERIMENTS

Monotonic and cyclic tensile tests were performed on dowelled connections in Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (CLT) made out of New Zealand *Radiata pine*. The connection layouts, based on Eurocode 5 provisions (EN 1995-1-1 2004) and models developed by Quenneville and Morris (2009), were designed to result in ductile and brittle responses with little margin between the different failure modes. Subsequently, the accuracy of the strength prediction and the mode cross-over was assessed. One connection layout was additionally

subjected to cyclic loading according to ISO 16670 (2003) to study the effects of cyclic loading on strength, ductility and mode cross-over.

TEST SET-UP AND MATERIALS

As shown in Fig. 3a, all CLT and LVL connection specimens were 610 mm long and 240 mm wide with a 20 mm slot to insert a 20 mm thick Grade 300 steel plate. The LVL specimens were 133 mm thick with a side member thickness of t_1= 56.5 mm. The CLT specimens were 130 mm thick with a side member thickness of t_1= 55 mm. The outer layers were 35 mm thick, whereas the cross-layers and inner layer were 20 mm thick.

The LVL specimens were grade LVL13 with a manufacturer specified Modulus of Elasticity (MOE) value of 13.2 GPa and a measured average moisture content of 8.4%. The veneers in the LVL specimens were 2.5 - 4.4 mm thick and glued with phenolic adhesive complying with AS/NZS 4357.0 (2005). The mean and characteristic (5^{th}-percentile) densities were ρ_{mean} = 591 kg/m^3 and ρ_k = 585 kg/m^3, respectively.

The CLT connection specimens had an average moisture content of 9.9%. Timber lamellas in the CLT specimens were 120 mm wide and glued with single-component polyurethane adhesive (PUR) without edge-gluing. The average MOE of the lamellas was 8 GPa in the outer layers and 6 GPa in the inner layers. The mean and characteristic density were ρ_{mean} = 443 kg/m^3 and ρ_k = 412 kg/m^3, respectively.

As shown in Fig. 3b, the top connection joining to the loading head was designed to be significantly stronger than the bottom connection subjected to destructive testing and consisted of six ϕ25 mm Grade 300 dowels reinforced with self-tapping screws. The bottom connection consisted of four chamfered ϕ20 mm dowels that were flush with the timber surface and were

sourced from the same batch as those tested in dowel bending and embedment. The connection was designed as described in the following section with different layouts targeting three different strength hierarchies in LVL, depending on the fasteners spacing a_1 and a_2, and the end distance a_3 and the edge distance a_4 as shown in Fig. 3c and Table 1:

- brittle row shear failure (RS) under monotonic loading $F_{EYMy} < F_{RSu} < F_{EYMu}$
- brittle group tear out failure (GT) under monotonic loading $F_{GTu} < F_{EYMy} < F_{EYMu}$
- ductile response under monotonic (DT-M) and cyclic (DT-C) loading $F_{EYMy} < F_{EYMu} < F_{BRu}$

The same layouts were adopted for the CLT specimens to study the reinforcing effect of the cross layers depending on the connection layout. It should be noted that the designations RS, GT, DT refer to the connection layout rather than the observed actual response from experimental testing. Five connection replicates for each layout were tested with a loading rate of 1 mm/s under monotonic loading and 10 mm/s under cyclic loading. The cyclic tests followed the ISO loading protocol (ISO 16670 2003), with the specimens being loaded to the target displacement of each cycle group and then returned to zero displacement. Each cycle group consisted of three repeated cycles whose target displacement was a certain percentage of the average Δ_u obtained from the monotonic tests. This was to represent a typical hold-down connection subjected to repeated uplifting in a seismic event. Displacements were measured with potentiometers at six different locations (front, back, two locations on each side) and averaged.

STRENGTH PREDICTION

Table 2 lists the characteristic strength properties of CLT, LVL, and the fasteners that served to calculate the connection's nominal strength, taken as the 5^{th}-percentile value of the strength distribution. All strength predictions were based on measured material properties rather than

129 supplier specified properties with the exception of the characteristic shear strength, $f_{v,k}$, and
130 characteristic tensile strength, $f_{t,k}$, which were provided by the CLT and LVL manufacturers.
131 As embedment strength values for CLT were not available, additional CLT embedment tests were
132 performed according to AS/NZS ISO 10984.2 (2015) and the characteristic embedment yield
133 strength, $f_{h,y,k}$, was determined from the load-deformation graphs according to EN 12512 (2013).
134 The relationship $f_{h,y,k} \approx 0.8\, f_{h,u,k}$ was established with $f_{h,u,k}$ being the characteristic ultimate
135 embedment strength (Ottenhaus et al. 2017). The characteristic embedment strength for the LVL
136 specimens was calculated according to Franke and Quenneville (2011) as
137 $f_{h,u,k} = 0.075(1 - 0.0037d)\, \rho_k$. Furthermore, three-point dowel bending tests were performed
138 according to AS/NZS ISO 10984.1 (2015) and the plastic yield moment was determined as
139 $M_{y,p}$ = 428,700 Nmm from which the elastic yield moment was calculated as $M_{e,p} = (6\pi/32)\, M_{y,p}$
140 (Ottenhaus et al. 2017).
141
142 The ductile strength prediction was based on the European Yield Model (EYM) as presented in
143 Eurocode 5 (EN 1995-1-1 2004). An attempt was made not only to predict the connection's
144 characteristic maximum capacity $F_{max,k}$ (equivalent to $F_{v,Rk}$, in Eurocode 5), but also to predict the
145 characteristic yield strength, $F_{y,k}$. The governing ductile mode was EYM VI (see Fig 2b). The
146 corresponding ductile capacity was calculated using Equations (1) and (2), simply referred to as
147 F_{EYMy} and F_{EYMu} in the following context.
148
149 The brittle strength prediction for LVL was adopted from Quenneville and Morris (2009) and
150 conservatively modified for accuracy, as shown in Equation (3) and (4). The calibration factors α_i
151 were adopted from Quenneville and Morris (2009). Currently, no expressions for the reduced

brittle strength due to dowel embedment, RS_{red} and GT_{red}, exist (Zhang et al. 2016). Therefore, it was unlikely to accurately represent the impact of this phenomenon on the brittle failure prediction.

$$F_{EYM\,y,k} = 4 \times 2\, f_{h,y,k_t} t_1 d \left(\sqrt{2 + \frac{4M_{y,e,k}}{f_{h,e,k} d t_1^2}} - 1 \right) \quad (1)$$

$$F_{EYM\,u,k} = 4 \times 2\, f_{h,u,k_t} t_1 d \left(\sqrt{2 + \frac{4M_{y,p,k}}{f_{h,u,k} d t_1^2}} - 1 \right) \quad (2)$$

$$F_{RS\,u,k} = 2n_2 \times \alpha_1 f_{v,k} k_{LS} (n_1 \min[a_1; a_3] - d) 2t_1 \quad (3)$$

$$F_{GT\,u.k} = 2 \times \alpha_1 f_{v,k} k_{LS} (n_1 \min[a_1; a_3] - d) 2t_1 + \alpha_2 f_{t,k} (n_2 - 1)(a_2 - d) 2t_1 \quad (4)$$

where k_{LS} = loading surface factor (0.65 for internal steel plate), α_1 = row shear calibration factor (0.84), α_2 = group tear-out calibration factor (1.26), a_i = fastener spacing (shown in Fig. 3c), d = fastener diameter, t_1 = single side timber thickness.

Table 3 gives the predicted connection strength values based on Equation (1) through Equation (4). Currently, there are no brittle strength predictions available for the CLT connections due to the crosswise layup of lamellas. However, the aim was to study the reinforcing effect of the cross-layers depending on different connection layouts. Therefore, the CLT specimen layouts were based on the LVL and the designations RS and GT were adopted for consistency.

EXPERIMENTAL RESULTS OF CLT CONNECTIONS

The CLT connections had 3-stages of response before failure:

1) Onset of dowel bending and yielding (Fig. 4a);

2) Continued yielding, out-of-plane bending of the timber members and onset of crack growth in cross layers (Fig. 4b). Shear failure in cross layer and separation of outer layer and cross layer close to the glue line;
3) Final brittle rupture in the outer layers (Fig. 4c and d).

Development of the second stage was influenced by the position of lamella edges in the outer layers and inherent imperfections such as knots and initial cracks. Furthermore, out-of-plane bending of the timber members and separation of the cross layer from the outer layer often caused premature brittle failure (Fig. 4e). The yield strength, F_y, of the load-displacement curves was defined according to EN 12512 (2013) with correction of some initial slip. This method was deemed appropriate as it does not produce a yield point for brittle behaviour (Brühl et al. 2011).

Table Tables 4 and 5 display the yield strength, F_y, maximum strength, F_{max}, strength at failure, F_u, initial stiffness, K, and the corresponding displacements Δ_y, Δ_{Fmax}, and Δ_u. The ductility was calculated as $\mu = \Delta_u / \Delta_y$ and the failure mode as well as the ductility classification were adopted from Smith et al. (2006): $\mu \leq 4$ brittle/low ductility (B), $4 < \mu \leq 6$ mixed (M), $\mu > 6$ ductile (D). The load-displacement curves and the strength predictions are shown in Fig. 5 and Fig. 6.

The load-displacement hysteretic curves for the DT-C specimens are shown in Fig. 7. It should be noted that RS01 and RS04 displayed high ductility as Δ_y was very small compared to Δ_{Fmax} and Δ_u. This would not be the case if another method such as Energy Equivalent Elastic Plastic (EEEP) method was used to establish Δ_y (Jorissen and Fragiacomo 2011, Brühl et al. 2011, Piazza et al. 2011). Another option to quantify ductility in a more meaningful manner is to use a combination of relative and absolute ductility definitions that can potentially also avoid the determination of the yield point as suggested by Flatscher (2016).

EXPERIMENTAL RESULTS OF LVL CONNECTIONS

For the LVL connection specimens, all DT-M, DT-C and RS specimens ultimately failed in row shear or tensile splitting with significant dowel yielding in bending. The GT specimens developed the expected group tear-out with little dowel bending (Fig. 8).

Tables 6 and 7 list the yield strength, F_y, peak strength, F_{max}, ultimate strength, F_u, initial stiffness, K, and the corresponding displacements Δ_y, Δ_{Fmax}, Δ_u. The yield point, failure mode and ductility were established with the same methods as for the CLT connections. The load displacement curves and strength predictions are displayed in Fig. 9 and 10. The hysteretic curves for the DT-C specimens are shown in Fig. 11.

DISCUSSION

The test results showed that the CLT and LVL connections with ϕ20 mm dowels can be designed to achieve good ductility (on average 6.2 – 14.6 from the ductile responses) and ultimate displacement capacity even if the connection is eventually governed by the mixed-mode response, as shown in Table 8. It should be emphasized that the achieved connection ductility does not equate system ductility or overall building ductility which requires the consideration of total building displacement (Moroder et al. 2014).

DUCTILITY IN CLT CONNECTIONS

Non-glued edges and gaps in the crosswise CLT layup affected the strength and resulted in high scatter of the test results. Therefore, it could be beneficial to spread out fasteners over a wider connection area to engage more cross layers and prevent brittle failure. Low rolling shear strength of the cross layers can cause separation from the outer layers and lead to brittle failure as the smooth steel dowels are not able to prevent opening up of the side members. Further investigations should also examine the influence of fastener spacing, edge distances and location of lamella gaps on ductility and brittle failure modes through comprehensive experimental research and/or robust finite element modelling.

For the CLT connections, the RS layout achieved twice as much ductility at the DT layout, which indicated that the increase of the end distance a_3 from 5d to 7d was very beneficial.

DUCTILITY IN LVL CONNECTIONS

The LVL connections can achieve very high ductility if edge distances are increased such that $F_{BRred} > F_{EYMu}$. However, this still requires quantification of the strength reduction, $F_{BRk,red}$, due to dowel embedment (Zhang et al. 2016).

The DT-M, DT-C layout and the RS layout achieved good ductility (average range of 6.2 – 9.8), whereas the GT layout failed before the onset of significant non-linear behaviour (average ductility of 2.5). The increase of edge distance a_3 from DT to RS improved the ductility in the LVL connections, although the effective shear plane length was reduced from $2 \cdot \min[a_1, a_3] - d$ = $2 \cdot 100 - 20 = 180$ mm to $2 \cdot 80 - 20 = 140$ mm.

If it is assumed that the initial stiffness, K, is independent of the connection layout, the yield displacement, Δ_y, should be identical for all connection layouts as the EYM strength is independent of the connection layout ($\Delta_y = F_{EYMy} / K$). As shown in Fig. 1, the DT layout should theoretically achieve a higher ultimate displacement, Δ_u, than the RS layout before mixed-mode failure occurs. Consequently, the DT layout's ductility, μ_{DT}, should be higher than the RS ductility, μ_{RS}, and the following expression should hold: $\mu_{DT} \geq \mu_{RS}$.

However, for the LVL specimens, the observed ultimate displacements were $\Delta_{u,DT} = 7.4$ mm and $\Delta_{u,RS} = 8.3$ mm, and the values for initial stiffness were $K_{DT} = 144$ kN/mm and $K_{RS} = 157$ kN/mm, which resulted in $\mu_{RS} > \mu_{DT}$. This finding suggests that the increased edge distances and fastener spacing might have an impact on the initial stiffness, K, and brittle strength reduction, $F_{BR,red}$. This issue should be further investigated.

CYCLIC AND MONOTONIC DUCTILITY

The CLT and LVL connection specimens showed increased ductility under cyclic loading: cyclic ductility was 1.15 times larger than monotonic ductility for the CLT connections, and 1.58 times larger for the LVL connections. This finding is in agreement with previous observations by Mohammad et al. (1998) but contradicts findings by Yasumura (1998). Therefore, the difference between cyclic and monotonic ductility should be further investigated with a larger sample size taking different displacement rates and loading protocols into account.

MODE CROSS-OVER

Table 8 compares the respective strength predictions ($F_{EYMy,k}$, $F_{EYMu,k}$, $F_{BRu,k}$) to the experimentally obtained average maximum values.

Mixed-mode response was observed in the DT layouts and brittle failure occurred before the ultimate ductile capacity, F_{EYMu}, was reached: $F_{EYMy} < F_u = F_{BRred} < F_{EYMu} < F_{BRu}$.

The strength predictions of the brittle layouts (GT and RS) in the LVL connections were conservative. Such conservatism is deemed appropriate due to the inherently high scatter in strength of brittle modes. However, too much conservatism should be avoided as it results in uneconomic designs.

It should be noted that the determination of F_y according to EN 12512 (2013) depends on the measured ultimate strength, F_u. Nevertheless, the prediction of F_y was fairly accurate for all the connection designs with the average error being within 10%. However, the error may be larger if all the supplier specified material properties were used for the strength predictions.

Ultimate and yield strength values achieved under cyclic loading were slightly higher than those under monotonic loading. As crack growth is dependent on time, this strength increase may be due

to the higher displacement rate under cyclic loading. However, this hypothesis should be verified further with a larger sample size for different displacement rates and loading protocols.

CONCLUSIONS

A total of 40 experimental tests were performed on dowelled CLT and LVL connections with three different layouts (ductile, row shear and group tear-out). Embedment tests on CLT and dowel bending tests were also performed to calibrate the input parameters for strength predictions of the connections.

The experimental results showed that the models for brittle failure (Quenneville and Morris 2009) were able to conservatively predict row shear failure and group tear-out failure in the LVL connection layouts. Given the high scatter in brittle modes, conservatism for brittle connection failure is deemed appropriate. However, better calibration of the model parameters could be performed to reduce some of this conservatism.

Purely ductile response ($F_u = F_{EYMu}$) was not achieved in the monotonic or cyclic experiments of the LVL connections as dowel yielding through bending was followed by row shear. This was due to the fact that the connection capacity decreases as the effective shear plane length is reduced by dowel embedment and timber densification underneath the dowel (Zhang et al. 2016, Novis et al. 2016). This mixed-mode response could not be reasonably predicted due to the lack of good prediction of the brittle strength reduction, F_{BRred}.

Brittle failure modes need to be further studied for dowelled CLT connections. Existing gaps in non-edge glued CLT can act as pre-existing shear failure planes which dramatically decrease connection strength and ductility. Low rolling shear strength of the cross layers may also lead to pre-mature failure which causes further strength reduction. However, if bolts were used as

fasteners, they could help prevent the out-of-plane bending and opening up of the side members in the connection. Nevertheless, there was an indication that the cross layers had a reinforcing effect for the CLT connections and good ductility (average ductility 7.3 – 14.6) was achieved if brittle failure was avoided.

Slightly higher yield and ultimate strength and slightly greater ductility were achieved under cyclic loading when compared to monotonic loading for both CLT and LVL connections (average of 8.4 vs 7.3 for the CLT connections and 9.8 vs 9.1 for the LVL connections). This indicates that it is possible to represent the cyclic backbone curves by the monotonic curves in terms of strength and ductility for dowelled connections that respond in a ductile mixed-mode manner. However, further experimental testing with a larger sample size, different connection layouts, displacement rates, and loading protocols is required to confirm this finding. Furthermore, a test series with purely ductile response is required to extrapolate this finding to completely ductile connection layouts.

The test results suggest that good ductility (on average 7.3 - 14.6) can be achieved for dowelled connections in LVL and CLT even if mixed-mode response is ultimately governing, as long as the connection layout is configured such that the ultimate ductile strength based on the European Yield Model is lower than the ultimate brittle strength $F_{EYMu} \leq F_{BRu}$. Further increase in connection ductile capacity could be achieved if the strength hierarchy for purely ductile response is targeted: $F_{EYMu} \leq F_{BRu,red}$.

In this study, EN 12512 was used to define the yield point as it does not produce a yield point for brittle failure. However, when the initial stiffness is calculated between 10% and 40% of the maximum load, the established yield displacement, Δ_y, can be very small which can lead to a misleadingly high ductility μ in some cases. Critical evaluation of the yield point and ductility definitions is required to give more rational ductility estimations.

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FIGURES

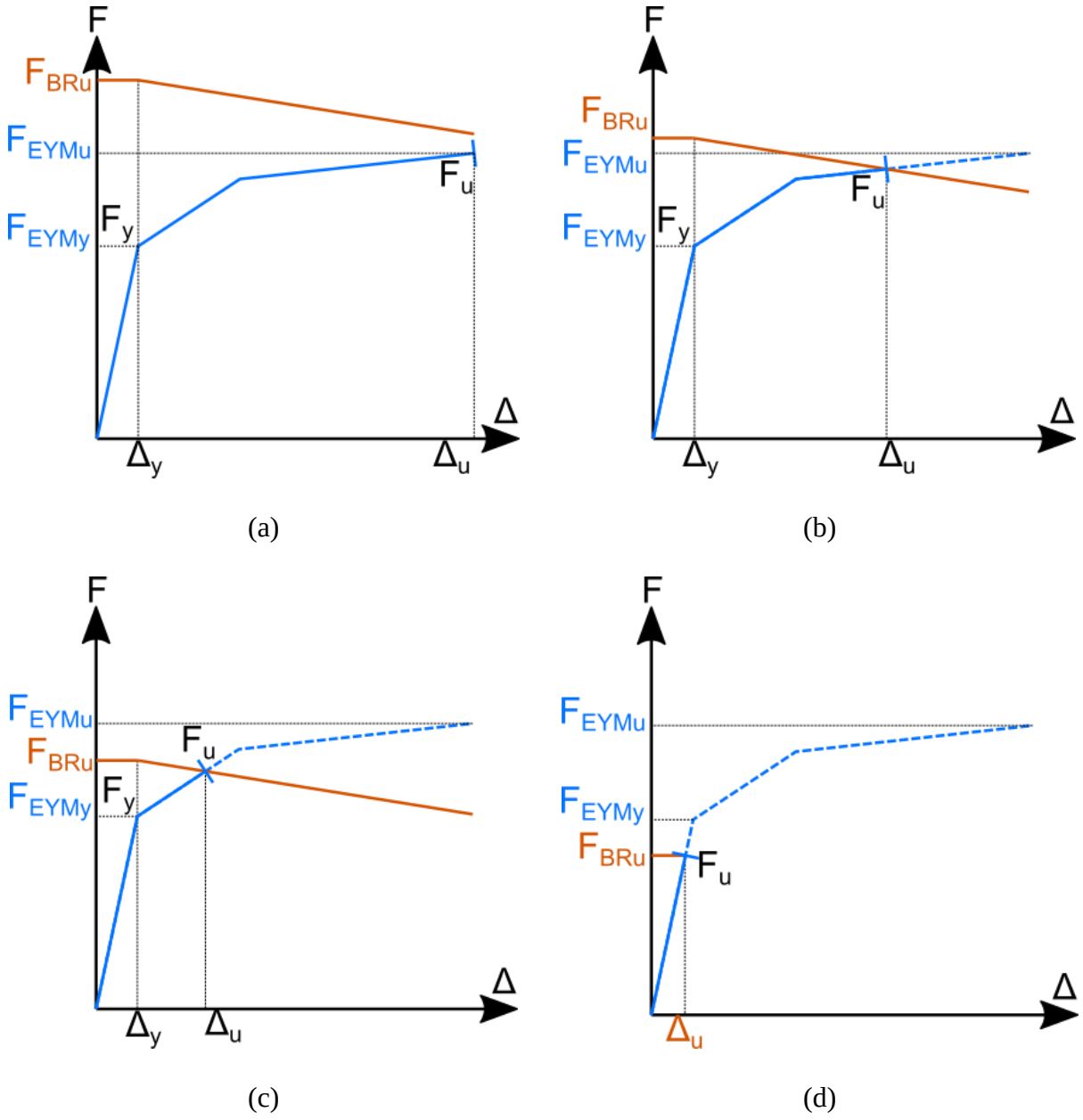
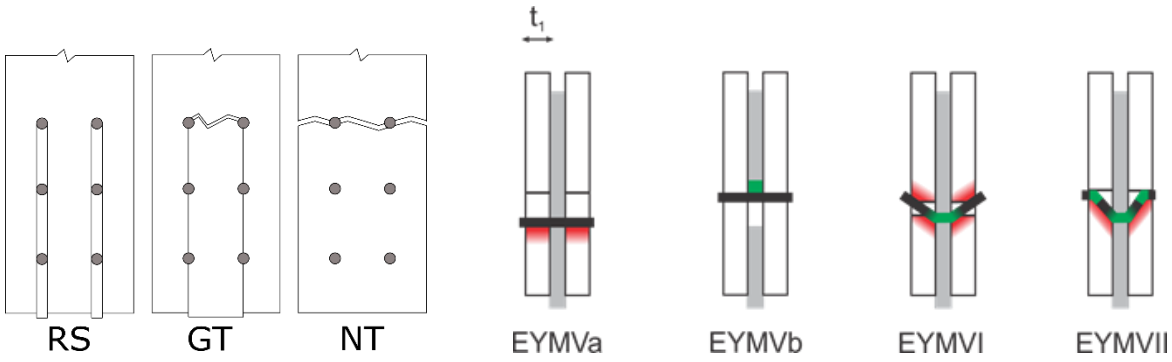
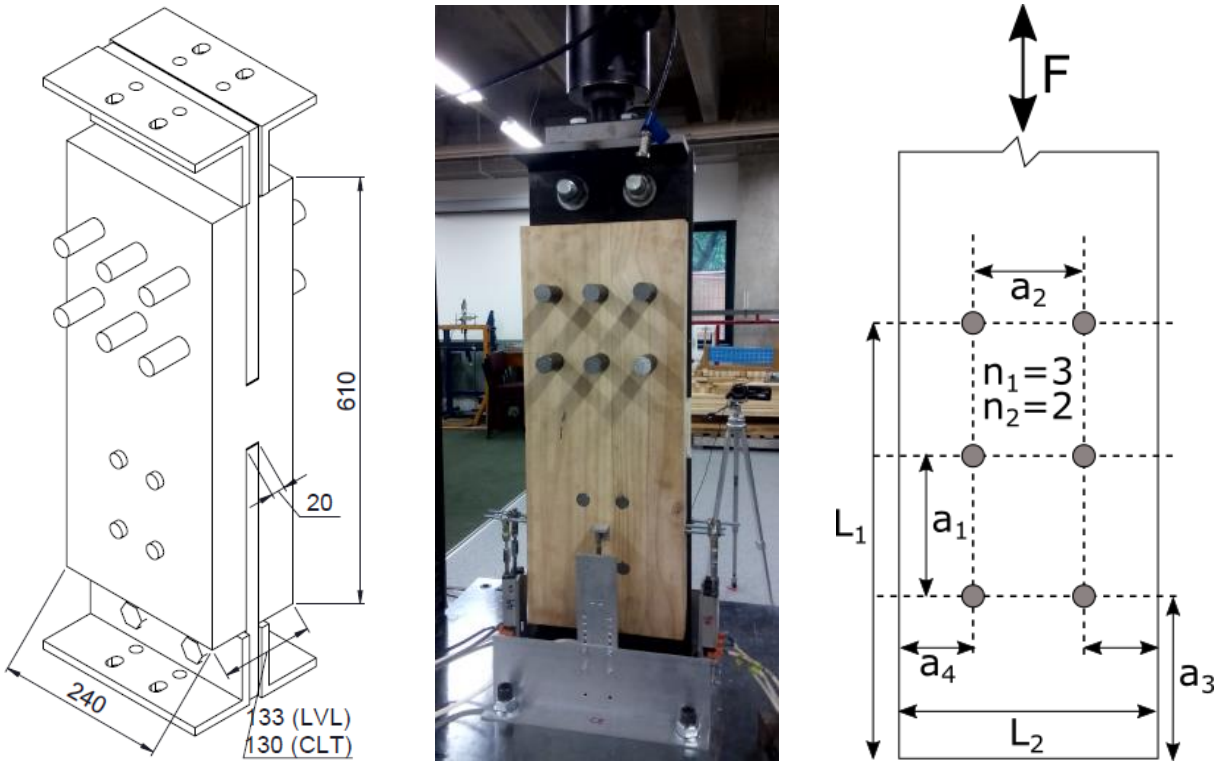


Fig. 1. Concept of mode cross-over from left to right: (a) Ductile, (b) ductile mixed-mode, (c) low ductility mixed-mode, (d) brittle



(a) (b)

Fig. 2. (a) Brittle failure modes (Row Shear, Group tear-out, Net tensile failure) (b) Ductile modes according to European Yield Model (red shows timber crushing, green shows steel yielding)



(a) (b) (c)

327 **Fig. 3.** (a) Layout and (b) set-up for monotonic and cyclic testing (c) fastener spacing

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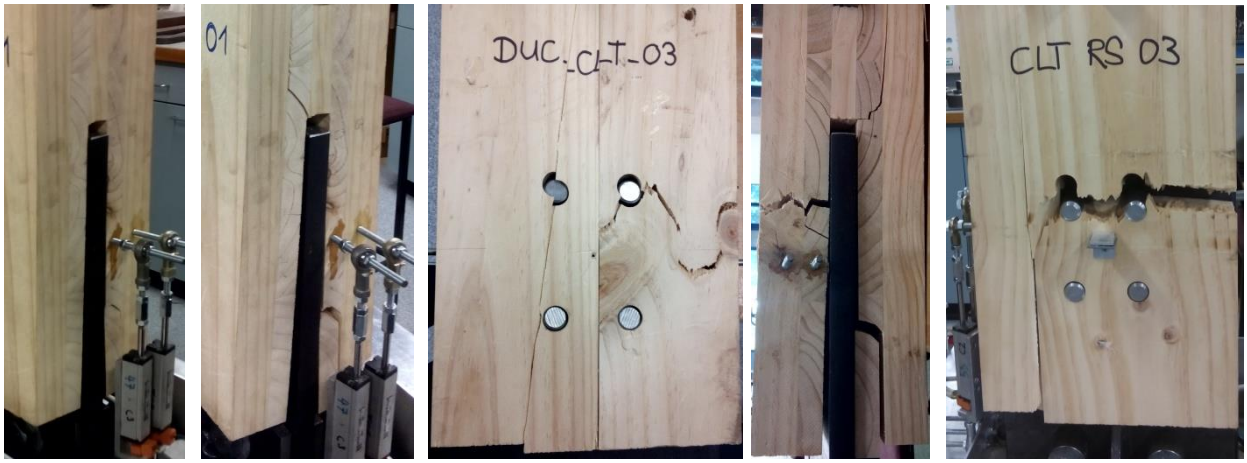
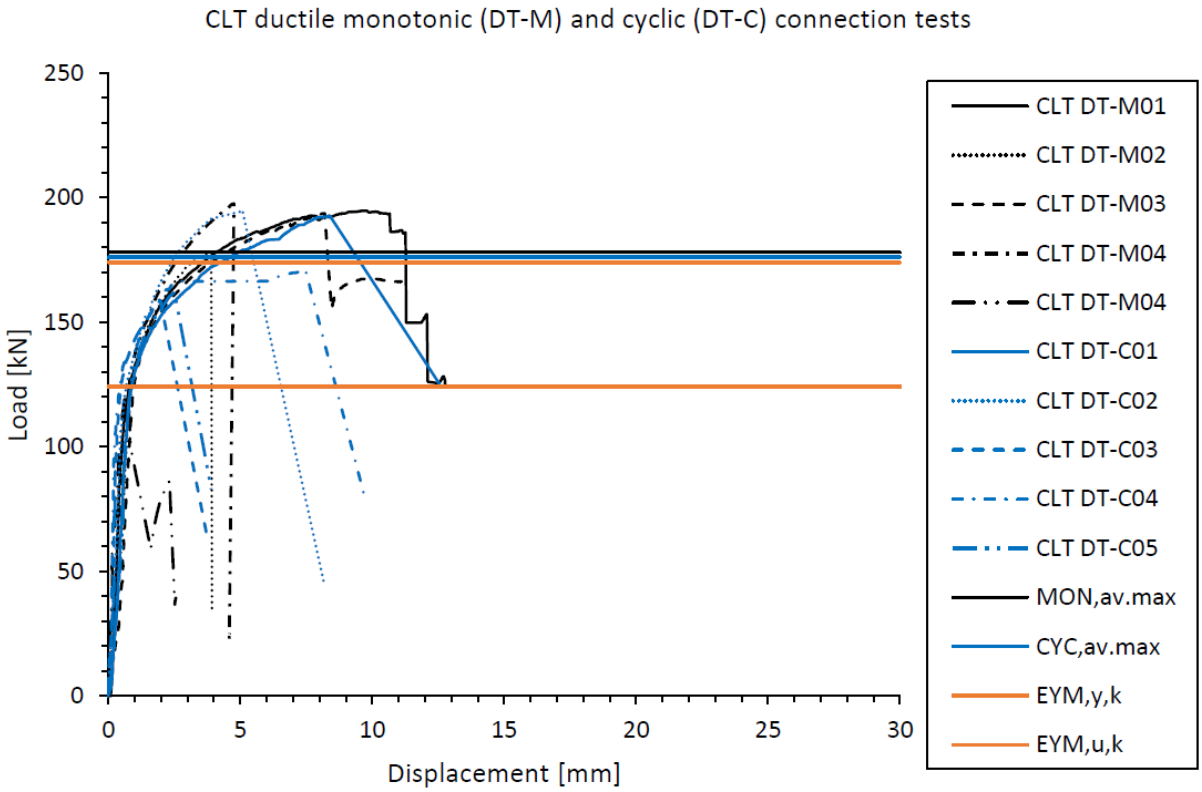


(a) (b) (c) (d) (e)

Fig. 4. Failure in CLT specimens from left to right: (a) onset of cracking in cross layer, (b) crack propagation, (c) DT layout failure front, (d) DT layout failure side, (e) RS layout failure



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333 **Fig. 5.** Load displacement curves of CLT connections with ductile layout

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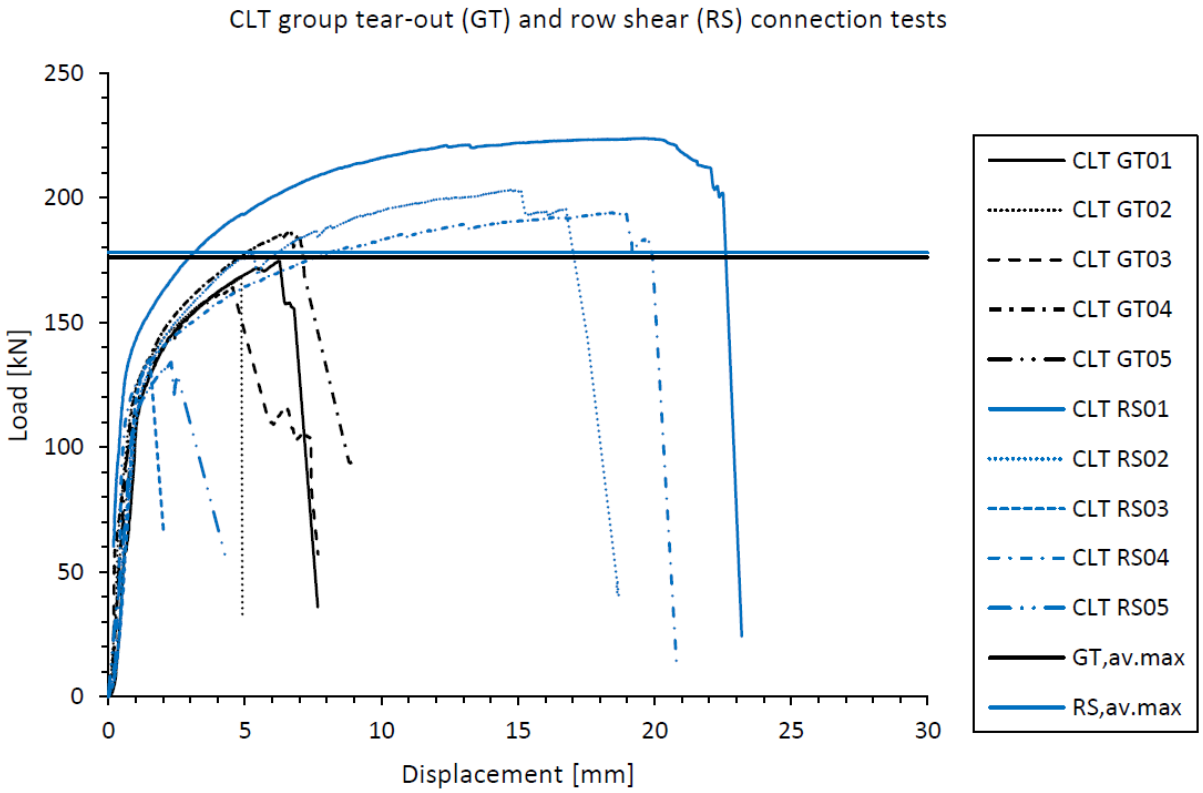

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336 **Fig. 6.** Load displacement curves of CLT connections with brittle layout

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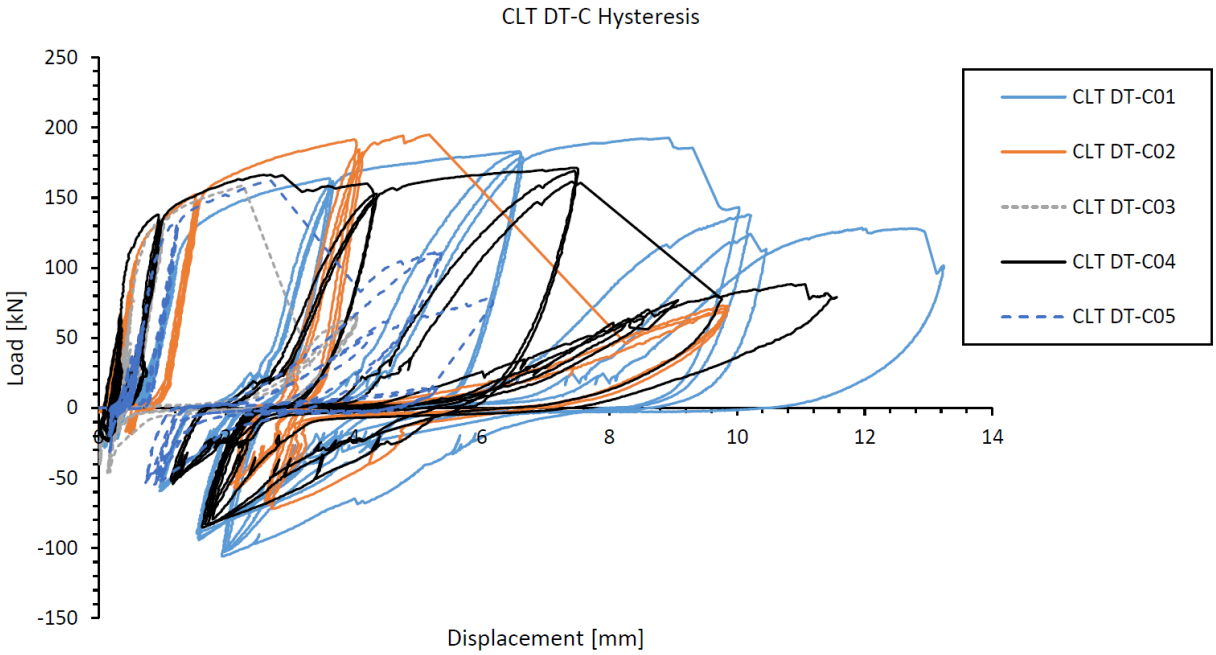

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339 **Fig. 7.** Hysteresis curves of CLT connections

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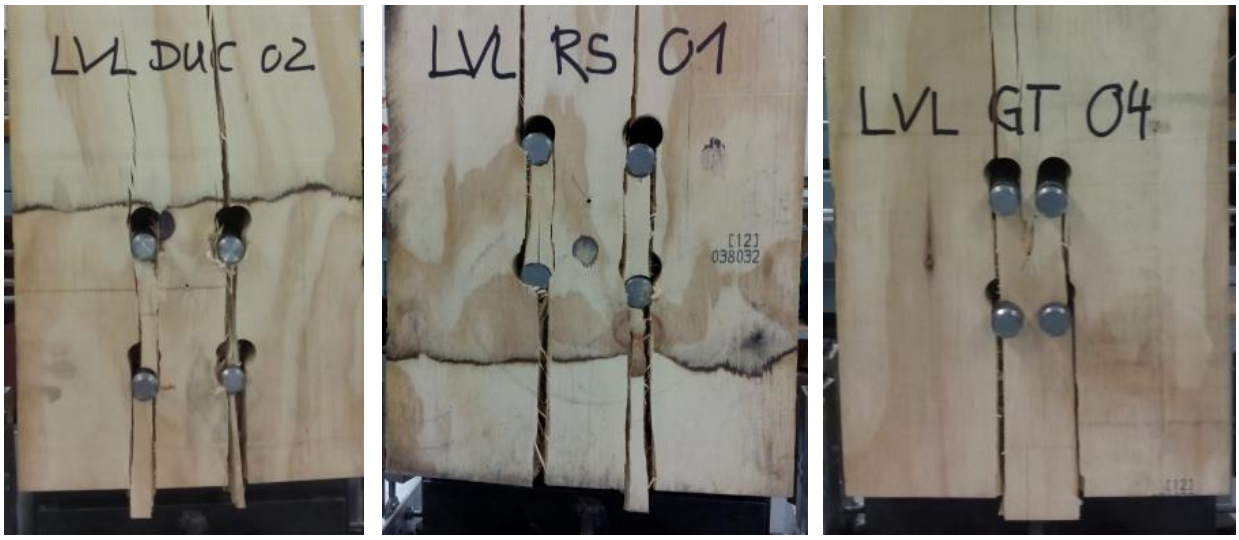

(a) (b) (c)

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342 **Fig. 8.** LVL failure: (a) Row shear in DT-C and (b) RS layout, (c) group tear-out in GT layout

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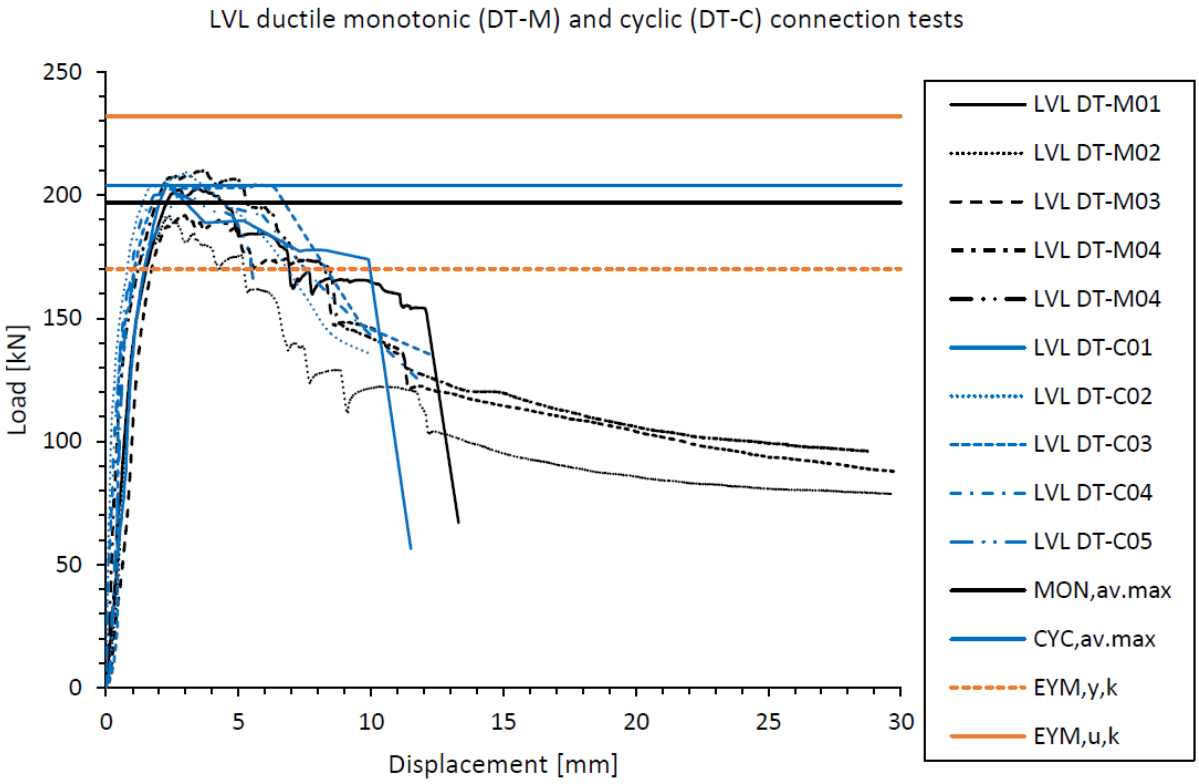
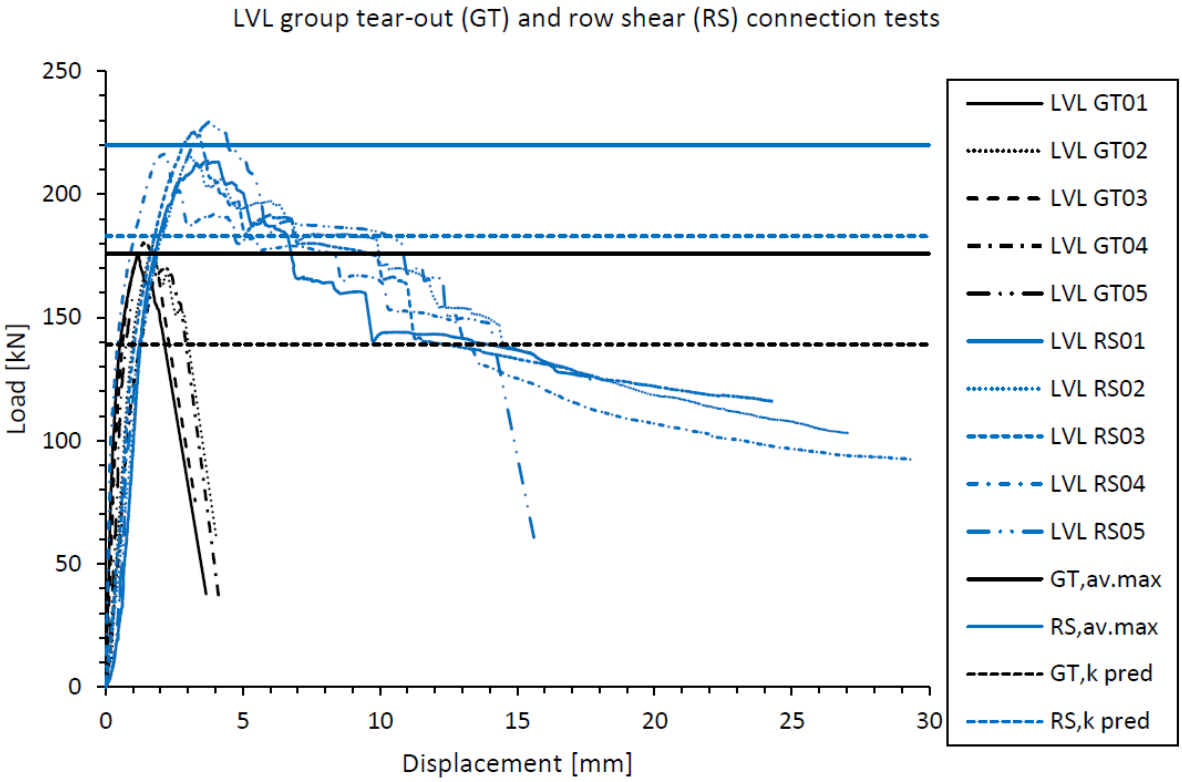


344

345 **Fig. 9.** Load displacement curves of LVL connections with ductile layout

346



347

348 **Fig. 10.** Load displacement curves of LVL connections with brittle layout

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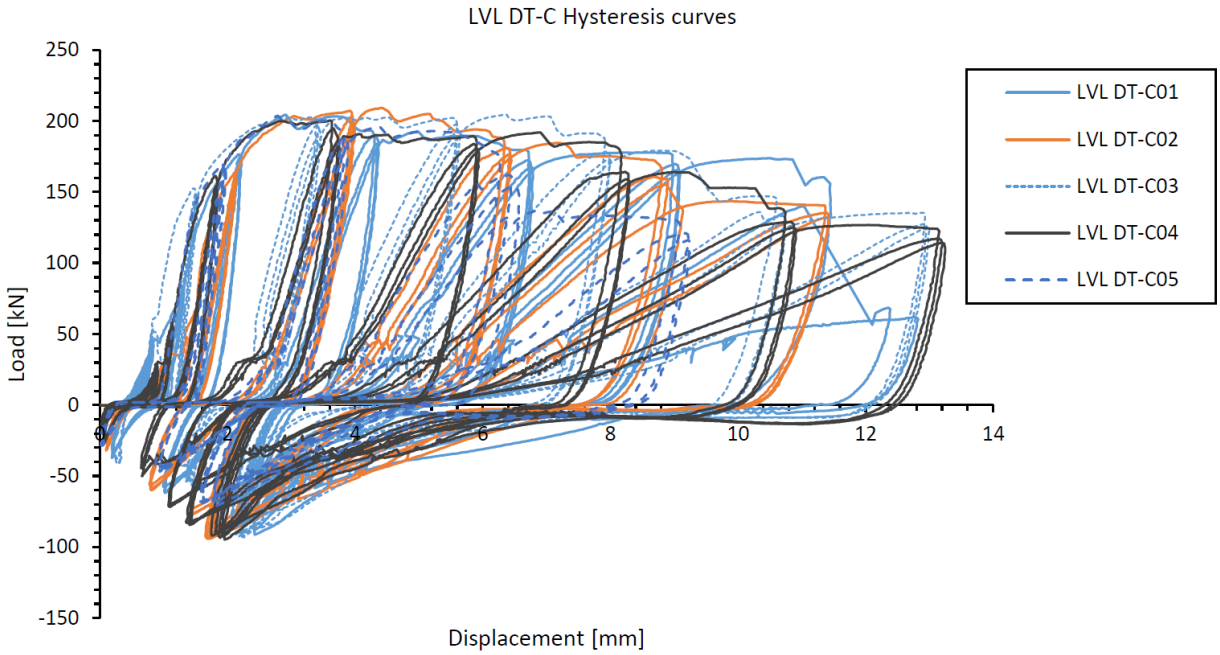

350

351 **Fig. 11.** Hysteresis curves of LVL connections

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TABLES

Table 1. Specimen layout

	Experimental layout				Design recommendations	
	Ductile layout	Brittle layouts			LVL	CLT
	DT-M / DT-C	RS	GT-CLT	GT-LVL	Eurocode 5	Handbook
a_1 [mm]	100/5*d*	80/4*d*	80/4*d*	80/4*d*	5*d*	4*d*
a_2 [mm]	60/3*d*	60/3*d*	40/2*d*	30/1.5*d*	3*d*	4*d*
a_3 [mm]	100/5*d*	140/7*d*	140/7*d*	140/7*d*	7*d*	5*d*
a_4 [mm]	90/4.5*d*	90/4.5*d*	100/5*d*	105/5.25*d*	3*d*	3*d*

Table 2. Characteristic strength properties for connection strength predictions

	$f_{v,k}$ [MPa]	$f_{t,k}$ [MPa]	$f_{h,y,k}$ [MPa]	$f_{h,u,k}$ [MPa]	$M_{y,p}$ [Nmm]	$M_{y,e}$ [Nmm]
LVL	5.30	33.00	32.50	40.63	428,700	252,525
CLT	3.80	8.80	20.85	26.06	428,700	252,525

Table 3. Strength predictions of connections with different layouts (DT-M: ductile monotonic, DT-C: ductile cyclic, RS: row shear layout, GT: group tear-out layout, NA: not available, governing mode printed in bold)

Force	CLT			LVL		
[kN]	DT-M / DT-C	RS	GT	DT-M / DT-C	RS	GT
$F_{EYMy,k}$	124	124	124	170	170	170
$F_{EYMu,k}$	**174**	174	174	**232**	232	232
$F_{RSu,k}$	NA	NA	NA	235	**183**	183
$F_{GTu,k}$	NA	NA	NA	306	280	**139**

Table 4. CLT DT layout test results (av. = average)

CLT	DT-M (ductile monotonic)						DT-C (ductile cyclic)					
test number	1	2	3	4	5	av.	1	2	3	4	5	av.
F_y [kN]	117	142	135	137	124	131	121	125	120	124	134	125
F_{max} [kN]	195	178	194	198	124	178	193	195	159	171	162	176
F_u [kN]	156	178	155	198	99	157	154	156	127	137	130	141
Δ_y [mm]	0.6	1.2	1.1	0.9	0.7	0.9	0.9	0.6	0.5	0.9	1.0	0.8
Δ_{Fmax} [mm]	9.5	3.7	8.2	4.8	0.7	5.4	8.5	5.1	2.0	7.5	2.4	5.1
Δ_u [mm]	10.9	3.7	8.5	4.8	0.8	5.7	9.2	5.9	2.4	7.9	3.0	5.7
K [kN/mm]	202	121	125	157	177	157	138	211	241	134	176	180
mode	D	B	D	M	B	M	D	D	M	D	M	D
$\mu = \Delta_u / \Delta_y$	18.8	3.2	7.8	5.5	1.1	7.3	10.5	10.0	4.7	8.6	8.2	8.4

Table 5. CLT GT and RS layout test results (av. = average)

CLT	GT (group tear-out)						RS (row shear)					
test number	1	2	3	4	5	av.	1	2	3	4	5	av.
F_y [kN]	123	106	106	119	130	117	125	117	129	120	122	123
F_{max} [kN]	175	168	164	187	186	176	224	203	136	194	134	178
F_u [kN]	140	168	131	149	149	147	179	163	109	155	107	143
Δ_y [mm]	1.2	0.5	0.6	0.8	1.2	0.9	0.9	1.0	1.2	0.8	0.9	0.9
Δ_{Fmax} [mm]	6.3	4.9	4.6	6.7	7.7	6.0	19.5	14.7	1.5	18.6	2.3	11.3
Δ_u [mm]	6.9	4.9	5.4	7.6	14.9	7.9	22.6	17.3	1.7	19.7	3.0	12.9
K [kN/mm]	103	197	186	145	111	148	136	120	108	158	139	132
mode	M	D	D	D	D	D	D	D	B	D	B	D
$\mu = \Delta_u / \Delta_y$	5.8	9.0	9.4	9.3	12.6	9.2	24.6	17.7	1.4	25.9	3.4	14.6

373 **Table 6.** LVL DT layout test results (av. = average)

LVL	DT-M (ductile monotonic)						DT-C (ductile cyclic)					
test number	1	2	3	4	5	av.	1	2	3	4	5	av.
F_y [kN]	184	163	184	159	178	173	163	167	130	178	158	159
F_{max} [kN]	203	192	192	210	190	197	205	209	204	200	201	204
F_u [kN]	162	153	153	168	152	158	164	167	164	160	161	163
Δ_y [mm]	1.3	1.1	1.7	0.9	1.3	1.2	1.2	0.9	0.6	0.9	0.8	0.8
Δ_{Fmax} [mm]	3.5	2.4	3.0	3.8	2.2	3.0	2.1	3.0	5.7	2.6	2.0	3.1
Δ_u [mm]	7.0	6.5	8.5	8.5	6.3	7.4	10.5	7.4	8.7	7.3	5.5	7.9
K [kN/mm]	142	148	108	186	137	144	141	196	232	198	211	196
mode	M	M	M	D	M	M	D	D	D	D	D	D
$\mu = \Delta_u / \Delta_y$	5.5	5.9	5.0	10.0	4.9	6.2	9.1	8.7	15.5	8.1	7.3	9.8

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376 **Table 7.** LVL GT and RS layout test results (av. = average)

LVL	GT (group tear-out)						RS (row shear)					
test number	1	2	3	4	5	av.	1	2	3	4	5	av.
F_y [kN]	176	151	174	154	155	162	181	196	186	145	155	160
F_{max} [kN]	176	180	181	170	172	176	214	215	225	216	229	220
F_u [kN]	141	144	145	136	138	140	171	172	180	173	184	176
Δ_y [mm]	1.2	0.9	1.6	1.2	0.8	1.1	1.6	1.9	1.4	0.6	0.8	1.1
Δ_{Fmax} [mm]	1.2	1.7	2.0	2.2	1.7	1.8	3.7	3.0	3.2	2.1	3.5	3.8
Δ_u [mm]	2.1	3.0	2.8	3.1	2.4	2.7	6.9	10.0	7.0	7.5	9.9	8.3
K [kN/mm]	147	168	109	128	194	149	112	104	136	242	194	157
mode	B	B	B	B	B	B	M	M	M	D	D	M
$\mu = \Delta_u / \Delta_y$	1.8	3.3	1.7	2.5	3.0	2.5	4.3	5.3	5.1	12.5	12.4	7.9

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Table 8. Average ductility and ultimate displacement of connection tests

	CLT				LVL			
	DT-M	DT-C	GT	RS	DT-M	DT-C	GT	RS
μ_{av} [-]	7.3	8.4	9.2	14.6	6.2	9.8	2.5	7.9
$\Delta_{u,av}$ [mm]	5.7	5.7	7.9	12.9	7.4	7.9	2.7	8.3
average mode	M	D	D	D	M	D	B	M

382 **Table 9.** Comparison of strength prediction with experimental results

		CLT		LVL	
		average maximum	predicted characteristic	average maximum	predicted characteristic
DT-M	F_y [kN]	131	124	173	170
	F_{max} [kN]	178	174	197	216
DT-C	F_y [kN]	125	124	159	170
	F_{max} [kN]	176	174	204	216
GT	F_y [kN]	117	124	162	170
	F_{max} [kN]	176	-	176	139
RS	F_y [kN]	123	124	172	170
	F_{max} [kN]	178	-	220	183

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NOTATIONS

$CYC_{av.max}$	cyclic average maximum strength
DT	ductile layout designation or strength
F_{BRred}	reduced brittle connection strength
F_{BRu}	ultimate brittle connection strength
F_d	design strength
F_{EYMu}	ultimate ductile connection strength based on European Yield Model
F_{EYMy}	connection's yield strength based on European Yield Model
F_{GT}	group tear-out strength
F_k	characteristic strength
F_{max}	connection's peak strength
F_{RS}	row shear strength
F_u	connection's ultimate strength
F_y	connection's yield strength / yield point
$GT_{av.max}$	group tear-out layout average maximum strength
K	initial stiffness
k_{LS}	loading surface factor (0.65 for internal steel plate)
$M_{y,e}$	fastener's elastic yield moment
$M_{y,p}$	fastener's plastic yield moment
$MON_{av.max}$	monotonic average maximum strength
$RS_{av.max}$	row shear layout average maximum strength

a_1	fastener spacing in row
a_2	fastener spacing between rows
a_3	edge distance in to loaded edge
a_4	edge distance to unloaded edge
d	fastener diameter
$f_{h,u}$	ultimate embedment strength
$f_{h,y}$	yield embedment strength
f_t	tensile strength
f_u	fastener ultimate tensile strength
f_v	shear strength
f_y	fastener yield strength
t_1	single side timber member thickness

α_1	row shear calibration factor (0.84)
α_2	group tear-out calibration factor (1.26)
Δ_{Fmax}	displacement at peak load
Δ_u	ultimate displacement / displacement at 80% of the maximum load
Δ_y	yield displacement
μ	ductility
ρ	timber density

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