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BONDED-IN RODS IN BEECH GLULAM – EFFICIENCY OF A RECESS IN THE BONDLINE

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ABSTRACT: The load-bearing behaviour of bonded-in steel threaded rods (BiR) in hardwood was investigated with special focus on the prevention of the splitting behaviour using a recess (not bonded zone) in the bondline. The main objective was to analyse the influence of the not-bonded length and the rod edge distance on the distribution of longitudinal shear and transverse tensile stresses in joints with bonded-in rods in beech glulam. Several BiR joint configurations were tested experimentally and a wide range of joint configurations with various combinations of recess and bonded lengths and edge distances were numerically investigated. According to the experimental and numerical analyses, a recess length of 2*d* (two times rod diameter) produced a significant positive effect on the stress distribution reducing the risk of splitting of beech glulam in the studied joint configurations.

KEYWORDS: Bonded-in rods, beech, splitting, not bonded length, numerical simulations, shear and tension interaction

1 INTRODUCTION

Discussions and ambition about the use of hardwood as construction material are currently present in Europe. On the one hand, hardwood provides excellent mechanical strength properties, but on the other hand, the strength parameters are less investigated and standardized for the design of connections with mechanical fasteners or bonded-in rods (BiR). The performance of connections in hardwood timber structures must be determined with high reliability to benefit from the naturally higher strength potential of hardwood. In Switzerland, 31 % of the entire wood stock is hardwood, where the biggest part with 18 % counts for beech wood [1]. Therefore, the research work concentrates on the European beech wood.

To use high-performing glued-laminated timber (glulam) from beech wood efficiently, high-performing connection systems must be available too. BiR connections are one of those. However, neither the Swiss standard SIA 265:2012 [2] nor the Eurocode 5 (EC 5) [3] currently include the design of BiR in softwood or hardwood glulam. The German national annex of EC 5 (DIN EN 1995-1-1/NA:2013-08) [4] provides a design method for axially loaded threaded steel rods glued in softwood. Research papers and publications have publicly discussed and proposed methods and approaches for the design of BiR, e.g., [5]. In EU, common rules for the assessment of BiR have been adopted in 2019 [6] and testing requirements for BiR in glued structural timber products have been adopted in 2021 [7]. Basic design provisions for GIR in timber connections are now given in EOTA TR 070 [8], and included in the Eurocode 5 draft [9].

The load-bearing capacity of BiR depends on the following main parameters [10]:

- Geometry; size and proportion of timber, adhesive and rod; slenderness; number and placement of rods (edge/end distances)
- Material stiffness and strength
- Fracture behaviour of timber and adhesive
- Variability of all properties
- Imperfections (quality control)
- Loading situation (forces, moisture, temperature)

For the best performance and robustness, it is preferable to prevent brittle failure modes, such as splitting, like shown in Figure 1, or bondline failures, and to target ductile steel failure. The maximum utilisation of timber (ratio of the connection capacity to the member cross-section capacity in tension) can be achieved by increasing the number of rods per unit area, which leads to smaller spacing and edge distances [11] and, in turn, may provoke

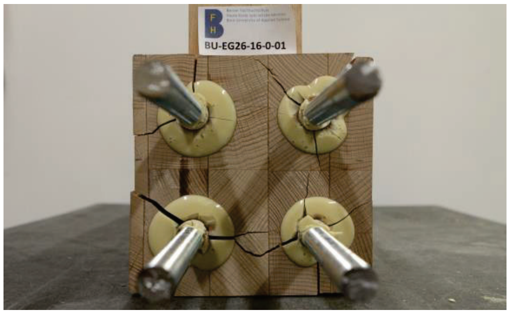

Figure 1: *Typical BiR failure in beech glulam – wood splitting due to transverse tension without a recess in the bondline*

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the undesirable wood splitting unless special preventive measures are undertaken.

This study is focused on achieving an efficient and robust connection configuration with small edge distances $a_{2,c}$ by using a recess l_{recess} in the bondline, i.e., not-bonded zone in front of the bondline, as shown in Figure 2. Therefore, the load-bearing behaviour depending on the interaction of the longitudinal shear and transverse tensile stresses around the bondline is investigated numerically and experimentally for beech wood glulam.

2 STATE OF THE ART

2.1 EFFECT OF BIR PLACEMENT

The placement, i.e., spacing and edge distance, have a great impact on the load-bearing capacity and performance of BiR connections [12], [13], [14]. By using the standardized spacing of 5d and steel with the tensile strength of 800 MPa results in an equivalent timber stress of 19.6 MPa which is about 60 % utilization for a timber grade GL40, as shown in Figure 3. The maximum utilisation up to 100 % can be achieved with a much smaller wood cross-section a_2 per rod between 3.61 and 3.85 times the rod diameter (d) for the timber grades GL 48 and GL 40 respectively. However, BiR connections with these small spacing and edge distances are not permitted in standards, because of their propensity for wood splitting and reduced pull-out strength even in laboratory tests.

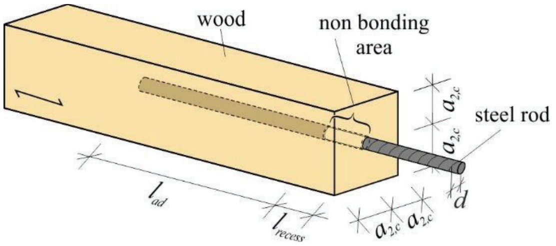

Figure 2: Principal sketch of BiR and notation of variables and components

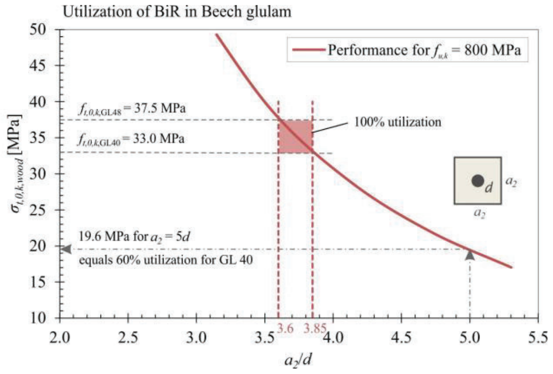

Figure 3: Utilization of BiR in beech glulam for steel strength of 800 MPa and different timber grades

For example, Figure 4 illustrates the influence of the edge distance on the pull-out resistance and failure mode of BiR connections in beech wood studied by Franke et al. [15]. Three levels of failure behaviour and capacity can be observed. At the edge distance $a_{2,c}$ (half of a_2) of 1.5d, the pull-out strength of rods, affected by the premature splitting, was about 20 % less than that of rods with 2.5d and 3.5d edge distance, for the same rod diameter, bonded length, and adhesive. Nevertheless, most of the joints with 2.5d edge distance experienced splitting and bondline failures at almost the same breaking loads. At 3.5d edge distance, there was no splitting observed and the strength of BiR joints reached the highest values with minimum variation. However, the cross-section utilisation of only less than 50 % can be achieved. All these tests were conducted on the BiR joints without a recess in the bondline.

2.2 EFFECT OF RECESS IN THE BONDLINE

It is well known that the stress distribution along the length of the BiR is not uniform, with stress concentrations near the ends of the bondline. Recently, Vallée et al. [16] studied the distribution of shear (τ_{RL}) and radial (σ_R) stresses along the bondline via numerical modelling of single BiR in CLT and glulam. Figure 5 illustrates the results for four different bonded lengths of a 12.7 mm (1/2-in) rod. The highest peaks of both shear and radial stresses are seen at the outer end of the bondline. These numerical simulations confirm that the longer the bondline, the greater is the difference between the peak stress and the mean stress, the less stress is transferred into the depth of the wood member, and, hence, the lower is the strength of the bondline.

The peaks of the shear and transverse tensile stresses near the end of the wood member negatively affect the pull-out resistance of BiR due to splitting. Fabris [12] studied the interaction of the stresses on the BiR performance and suggested that a recess of the bondline into the wood creating an unbonded zone near the outer end increases the stressed wood volume around the rod and hence improves the resistance to splitting, as shown in Figure 6.

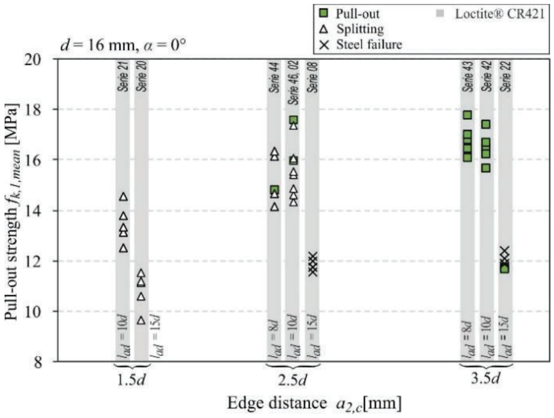

Figure 4: Pull-out strength and failure modes of BiR in beech glulam for different edge distances [15]

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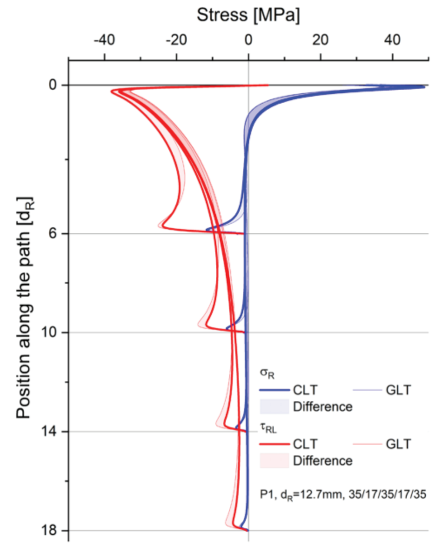

Figure 5: *Shear stresses, τ_{RL}, and radial stresses, σ_R, along the adhesive-wood interface, reference load F_0= 100 kN, from [16]*

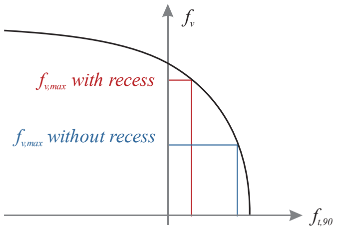

Figure 6: *Interaction of shear and transverse tensile stresses, modified from [12]*

The beneficial effects of a recess in the bondline on the pull-out resistance has been demonstrated experimentally by Salenikovich et al. for BiR in CLT [17] and in glulam [18]. It allowed achieving a higher load capacity and minimizing the risk of splitting and other brittle failure modes, such as plug shear in CLT for rods bonded perpendicular to the grain.

The effect of different recess lengths in beech glulam has not been investigated so far. Besides the increase of the stressed wood volume around the rod, it is assumed that a recess in bondline also changes the interaction of shear and transverse tensile stresses as indicated in Figure 6 and leads to higher capacities. Less transverse stress will exist at much higher shear stress for the case with a recess.

3 INVESTIGATION OF THE RECESS LENGTH

3.1 MATERIALS

All specimens for the investigation have been produced from Glulam GL 40h of European Beech (*Fagus sylvatica*) from Swiss forests with an average density of 710 kg/m³ and moisture content of 10.5 %. Threaded steel rods of M16 with a strength class of 8.8 and 10.9 were bonded-in using a two-component PUR adhesive Loctite® CR421 or its newer version Loctite® CR821. Centering aids and upright position gluing was used, see Figure 7.

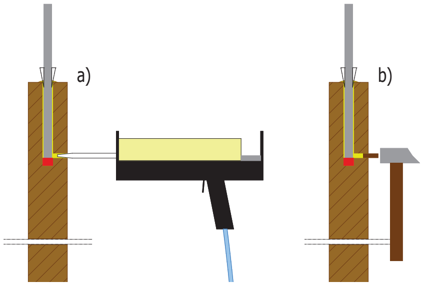

Figure 7: *Preparation of test samples, a) gluing injection from the bottom of the bondline, b) closing of the injection hole with wood dowel*

3.2 EXPERIMENTAL PROGRAMME

The investigation was carried out in two stages. The first stage started within a research project on efficient connections in hardwood [15], see Table 2. It focused on testing of known connection systems in hardwood to determine their performances. Within the test period from 2019 to 2021, the adhesive was changed from Loctite® CR421 to CR821 in line with current market developments at Henkel & Cie AG and the borehole diameter d_{hole} was reduced by half, from d_{BiR} + 4 mm to d_{BiR} + 2 mm. The experimental programme included a variation of the edge distance $a_{2,c}$ and the bonded length l_{ad} in combination with a recess length of 0d, 2d or 5d which reflected the known practice for softwood glulam.

The second stage stemmed from the first one and focused specifically on the influence of the recess length on the performance and comprised test series S0 to S5 with the recess length between 0d and 5d in increments of 1d. A constant edge distance of 1.75d and bonded length of 13d were used to provoke splitting failure and prevent pull out failure. In the second stage all rods were bonded-in with Loctite® CR821. Table 2 summarizes the configurations and variations of the experimental test programme.

3.3 NUMERICAL SIMULATIONS

The influence of the not-bonded length on the resistance of a BiR joint was also studied using numerical linear elastic simulations of the joint as shown in Figure 2, with a single rod with a varying bonded length l_{ad}, recess length l_{recess} and edge distance $a_{2,c}$. The numerical investigation focused on the analysis of the stress distributions along the bondline and especially at the beginning of the bondline of a single rod connection in beech glulam. A quarter of the specimen was modelled benefiting from the double symmetric conditions, as shown in Figure 8 for a connection with a bonded length of 13d, recess length of 1d and edge distance $a_{2,c}$ of 2.5d. The elastic material properties are summarized in Table 1. The rod was loaded in tension by 100 MPa for all simulations and presented results.

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Table 2: *Experimental programme of BiR with the rod diameter of M16*

Stage	Series	Number of tests	Adhesive Loctite®	d_{hole} [mm]	$l_{ad} + l_{recess}$ [-]	$a_{2,c}$ [-]	Failure		
							Splitting	*Pull-out*	*Steel rupture*
1	02, 46	9	CR421	20	10*d* + 0*d*	2.5*d*	7	2	-
	07	5	CR421	20	10*d* + 2*d*	2.5*d*	-	4	-
	08	5	CR421	20	15*d* + 0*d*	2.5*d*	-	-	5
	20	5	CR421	20	15*d* + 0*d*	2.5*d*	5	-	-
	21	5	CR421	20	10*d* + 0*d*	1.5*d*	5	-	-
	22	5	CR421	20	15*d* + 0*d*	3.5*d*	-	2	3
	42	5	CR421	20	10*d* + 0*d*	3.5*d*	-	5	-
	43	5	CR421	20	8*d* + 0*d*	3.5*d*	-	5	-
	44	5	CR421	20	8*d* + 0*d*	2.5*d*	4	1	-
	M15	3	CR421	18	10*d* + 5*d*	2.5*d*	-	3	-
	M09, M16	8	CR821	18	10*d* + 0*d*	2.5*d*	-	8	-
	M13, M17	7	CR821	18	10*d* + 5*d*	2.5*d*	-	7	-
	M22	3	CR821	18	10*d* + 5*d*	1.5*d*	-	3	-
2	S0	4	CR821	18	13*d* + 0*d*	1.75*d*	2	-	2
	S1	4	CR821	18	13*d* + 1*d*	1.75*d*	1	3	-
	S2	4	CR821	18	13*d* + 2*d*	1.75*d*	-	3	-
	S3	4	CR821	18	13*d* + 3*d*	1.75*d*	-	1	3
	S4	4	CR821	18	13*d* + 4*d*	1.75*d*	-	-	4
	S5	4	CR821	18	13*d* + 5*d*	1.75*d*	-	-	4

Table 1: *Elastic material properties*

Component	Young's modulus [MPa]	Poisson ratio [-]	Shear modulus [MPa]
Beech, longitudinal	14'500	0.04	1'000
Beech, transverse	1'100	0.61	380
Adhesive, CR821	2'850	0.37	1'040
Steel rod	210'000	0.30	81'000

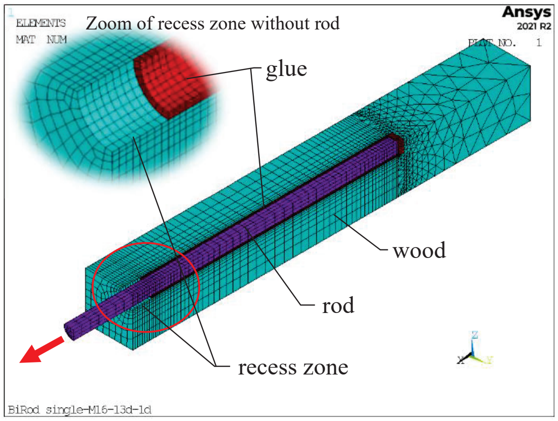

Figure 8: *FE model of a BiR joint, l_{ad} =13d, l_{recess} = 1d*

3.4 EXPERIMENTAL RESULTS

All failure modes, steel rupture (yielding of the rods), wood splitting and rod pull-out (bond rupture), were observed. The failure modes and pull-out strength values calculated from the maximum load divided by the circumference with the nominal rod diameter and the bonded length are summarised in Figure 9.

In general, the BiR joints glued with Loctite®CR821 demonstrated a lower pull-out strength compared to Loctite®CR421. Therefore, the results are analysed separately.

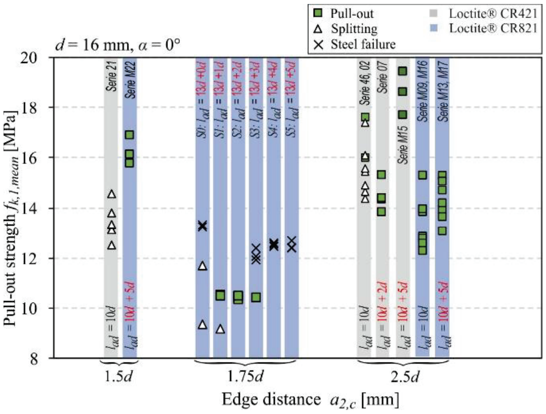

Figure 9: *Pull-out strength results depending on the edge distance, bonded length and recess length for two glues*

Focusing on Loctite®CR421 (columns highlighted in grey):

- Splitting was not observed in joints with the recess length of 2*d* (series 07) and 5*d* (series M15) and the edge distance of 2.5*d* as opposed to joints without a recess (series 46 and 02); the joints with the recess of 5*d* showed higher strength.

Focusing on Loctite®CR821 (columns highlighted in blue):

- Splitting was not observed in joints with the edge distance of 2.5*d* without a recess (series M09 and M16) and with a recess of 5*d* (series M13 and M17); however, less variation and higher mean values were observed for the series with recess.
- No splitting was observed even for the joints with the edge distance of 1.5*d* with the recess of 5*d* (series M22).
- All joints with the bonded length of 13*d* and the edge distance of 1.75*d* (series S0 to S5) showed lower pull-out strength values than those with the bonded length of 10*d* and the edge distance of 2.5*d* (due to the larger bondline circumference).

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- Three distinct levels of pull-out strength and failure mode transition can be observed depending on the length of the recess:
    - Although two specimens without a recess (series S0) showed steel failure, two specimens failed by splitting, one of which occurred at a low load level; one specimen with the recess of 1*d* (series S1), failed by splitting at a similar load level.
    - Specimens with the recess length of 1*d*, 2*d* and 3*d* (Series S1, S2, S3) that failed by pull-out (bond failure) showed equal pull-out strength, which was higher than that due to splitting but less than that due to the rod rupture.
    - Starting with the recess length of 2*d* (Series S2), no splitting failures were observed.
    - Three specimens with the recess length of 3*d* (Series S3) reached the steel rod resistance.
    - All specimens with a recess length of 4*d* (Series S4) and 5*d* (Series S5) failed due to steel rod rupture.

3.5 NUMERICAL RESULTS

Figure 10 shows a BiR joint FE model in a deformed state and the deformation gradient in the longitudinal direction for the bonded length of 13*d* and the recess length of 1*d*. The resulting shear and transverse stress distributions along the bondline at the wood/glue interface are plotted for the same joint configuration in Figure 11 and Figure 12, respectively. The stress distributions for the recess length between 0*d* and 4*d* (no visible difference was observed for 5*d*) are summarized in Figure 13 and Figure 14.

The numerical simulations show a 19% increase of the longitudinal shear stress from 0*d* to 2*d* recess length and then a gradual increase up to 26.3% at 5*d* (see Figure 14 and Figure 15). At the same time, the transverse tensile stress at the beginning of the bondline drops down rapidly to 47.5% from 0*d* to 2*d*, and to 46.5% at 3*d* (see Figure 13 and Figure 15). No further reduction of the peak transverse stress is observed beyond $l_{recess} = 3d$.

Similar results were observed in simulations with a bonded length of 10*d* and for connections in softwood.

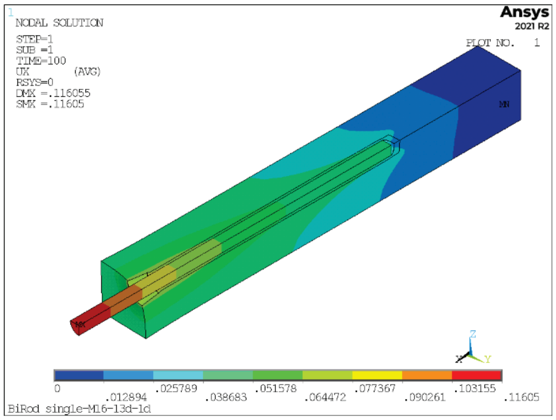

Figure 10: *Deformations of a BiR joint,* $l_{ad} = 13d$*,* $l_{recess} = 1d$

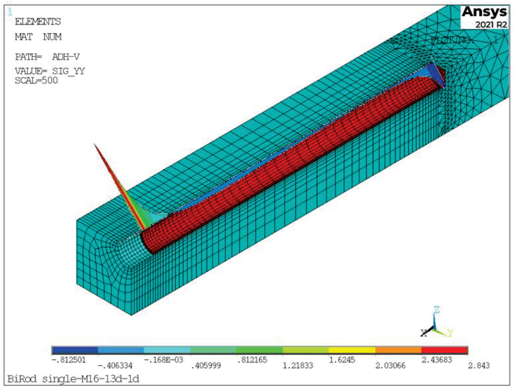

Figure 11: *Transverse stress distribution along the bondline,* $l_{ad} = 13d$*,* $l_{recess} = 1d$

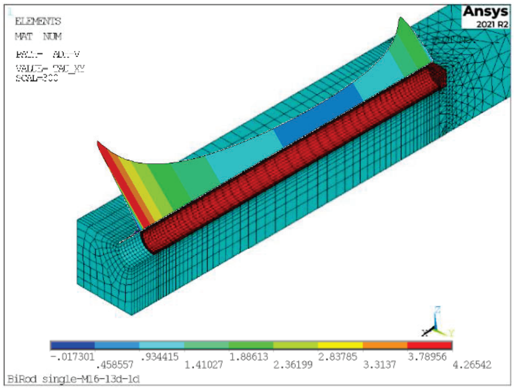

Figure 12: *Shear stress distribution along the bondline,* $l_{ad} = 13d$*,* $l_{recess} = 1d$

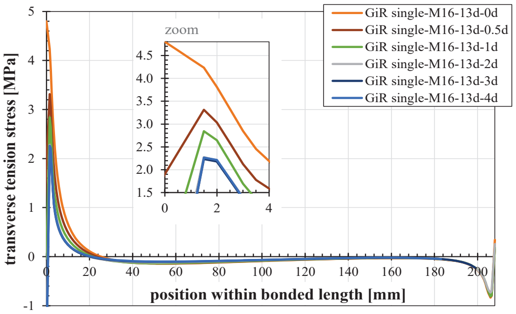

Figure 13: *Transverse stress distribution along the bondline depending on the recess length*

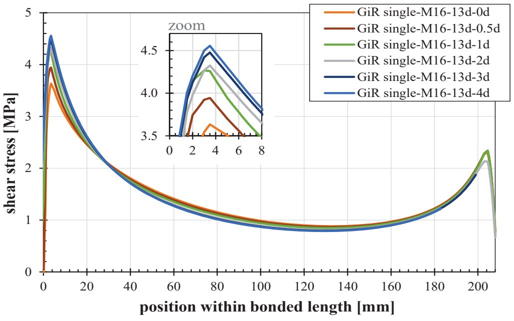

Figure 14: *Shear stress distribution along the bondline depending on the recess length*

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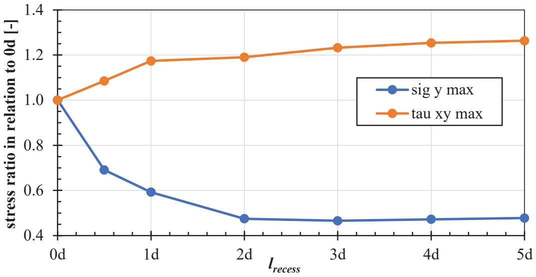

Figure 15: *Increase and decrease of the maximum transverse tensile and shear stresses at the beginning of bondline depending on the recess length*

4 DISCUSSION AND CONCLUSION

From the experimental results it can be concluded that without a recess or with a recess less than 2*d*, the risk of wood splitting in BiR joints with reduced spacing is very high. With a recess of 3*d* and more, the bondline strength increases to the extent that allows reaching the steel rod rupture, which is a preferred failure mode for BiR connections.

These experimental observations are well aligned and explained by the numerical simulations, which show a significant reduction of the peak transverse tensile stress at the recess length of 2*d*. It can also be concluded that no further gain in the splitting resistance is expected when the recess length is beyond 3*d*.

The relation assumed in Figure 6 can be confirmed by summarizing the stress relationship/interaction of shear and transverse tension depending on the recess length in Figure 16. The mean shear strength of 12 MPa and mean transverse tension strength of 7 MPa were assumed for beech wood according to [19]. Up to the recess length of 2*d*, higher shear stresses in combination with lower transverse tensile stresses can be achieved before failure with the increasing recess length. Therefore, the propensity for splitting is reduced and a higher axial load can be applied on the bonded-in rod. No further significant change is observed beyond $l_{recess} = 2d$.

These observations can be confirmed by using equation (1) for the stress verification, which is illustrated in Figure 17 for the GiR joint with bonded length of 13*d* under the same stress of 100 MPa. An optimal utilization starts at a recess length of 2*d*. However, a recess length of 3*d* is recommended for the safety reason before further confirmation with more experimental and numerical results including long-term load and moisture fluctuation effects.

$$\left(\frac{\tau_{yz}}{f_v}\right)^m + \left(\frac{\sigma_y}{f_{t,90}}\right)^n \leq 1 \tag{1}$$

where

τ_{yz}	shear stress [MPa]
f_v	shear strength [MPa]
σ_y	transverse tensile stress [MPa]
$f_{t,90}$	transverse tension strength [MPa]
m	interaction parameter [-]
n	interaction parameter [-]

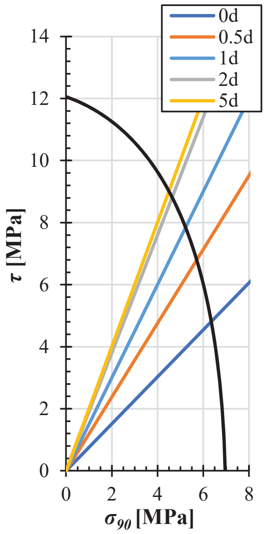

Figure 16: *Stress interaction development curves at the beginning of the bonline in relation to the recess length and in comparison with the failure criteria considering the interaction of shear and transverse tensile stresses*

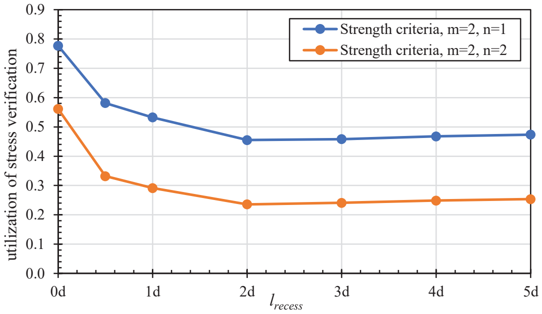

Figure 17: *Utilization of the shear and transverse tensile stress verification for two failure criterias curves (steel rod rupture is not included)*

Further investigations will be done towards

- Probabilistic verification of the timber stress interaction near the beginning of the bondline to analyse the contribution of the wood volume in front of the bondline;
- Implementation of fracture mechanics into the numerical simulations;
- Variations of material parameters as well as geometric parameters; and
- Experimental testing for more statistical values and validation.

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