TENSION-LOADED CONNECTIONS WITH WOOD DOWELS

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ABSTRACT: Wood dowels carry tremendous opportunities concerning their application as fasteners and connection elements. Aspects such as sustainability and homogeneous recyclability can be addressed very well by using them to an increasing degree. Although they have been quite common for carpenters for hundreds of years, several characteristics need to be clarified systematically from an engineering point of view.
In this context, results and further investigations are presented within this paper. The load-bearing behaviour of beech dowels under tension force is subject to pull-out and shear testing. Both the inclination angle and the penetration length as major parameters are varied. The interrelation between the inclination, failure loading and ductility of wood dowels is not linear. This finding should be considered when designing and dimensioning new segmented cross-sections.

KEYWORDS: wood dowel, fastener, pull-out test, shear test, inclined connection

1 INTRODUCTION

1.1 HISTORIC AND CURRENT APPLICATIONS

Connections with wooden fasteners are one of the oldest techniques for connecting load-bearing elements. This type of pin-shaped fastener has often been found in historical structures. There, they serve to secure the position of carpenter's joints and transfer connection forces. In this application, the dowel connection is subjected to shear and tension forces [1] [2].
After having been replaced by steel fasteners in recent decades, wood dowels are now back in focus, even outside the rehabilitation of cultural heritage [3] [4]. Wood dowels could be a viable alternative, especially where the use of steel fasteners is critical. Their usage in salt silos, where metal fasteners would be exposed to chemical attack or the amount of electrically conductive material is to be reduced, offers several advantages. In addition, wood dowels have the same favourable properties in case of fire as structural timber. [5]

1.2 FUTURE PROSPECTS

A new aspect is the increasing potential of digital manufacturing methods. Complicated joint geometries are no longer a challenge, which means that, together with the geometry, the performance of wood dowels can be optimally utilised. In this context, the use of robotically manufactured composite components with wood dowels is being researched at the University of Kassel.
It has become clear through the planning and production on a prototype basis that questions regarding the load-bearing behaviour of wood dowels cannot be completely clarified by the relevant literature. The combination especially of tension and shear load has not been studied previously.

2 TEST SERIES 1

2.1 GENERAL INFORMATION

The main focus of the experimental investigations within the first test series is on evaluating the influence of the inclination angle of the fasteners. Therefore, pull-out and shear tests are conducted for different set-ups.
In order to get some statistical background for the research, each single test is repeated five times. Two different material combinations are additionally considered for the pull-out testing. Together with the four angles selected – α = 0°, 15°, 30° or 45° – this leads to 40 pull-out and 20 shear tests.
Both the diameter ($d_{fastener}$ = 10 mm) and the length ($\ell_{fastener}$ = 70 mm) of the wooden dowels are constant for test series 1. The penetration lengths $t_{h,1} = t_1$ and $t_{h,2} = t_e$ correspond to each particular set-up and are dependent on the specific test.
Regarding the style of presenting the experimental results, the single test results are marked as "X", the coloured columns represent the bandwidths and range, and the dotted lines show the mean values as well as the 5 % quantile in the following diagrams.
In the case where single values are identified as outliers, they are displayed as "X", and are not considered for the columns.
Outliers are identified according to the following rules. Results lower than 50 % of the mean value of the three medium results and higher than 150 % of the mean value of the three medium results are treated as outliers and, therefore, neglected.
As an example, the steps of this methodical approach are described for the results Series 1 – Pull-out test – max Force – LVL/LVL – α = 0° (see Figure 5). The single test results are given in Table 1.

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***Table 1:** Pull-out test – exemplary results for laminated veneer lumber (LVL)/LVL – α = 0°*

	test number				
	1	2	3	4	5
F_{max} [N]	268	677	466	347	357

As the data in Table 1 show, the minimal and maximal failure load measured occur for test $n = 1$ and $n = 2$. Neglecting these two results, the mean value of the remaining three tests produces $F_{outlier}^{mean} = 0.390$ kN, see (1).

$$F_{outlier}^{mean} = (466 + 347 + 357)/3 = 390\ N \quad (1)$$

The upper and the lower limit can be calculated as $F_{outlier}^{upp} = 0.585$ kN and $F_{outlier}^{low} = 0.195$ kN, see (2) and (3).

$$F_{outlier}^{upp} = 1{,}5 \cdot 390 = 585\ N \quad (2)$$

$$F_{outlier}^{low} = 0{,}5 \cdot 390 = 195\ N \quad (3)$$

Comparing these values with the experimental results, test $n = 2$ ($F_{max} = 0.677$ kN) exceeds the bandwidth and is, therefore, identified as an outlier.

Out of the remaining four results, the mean value, the variance and the coefficient of variation (COV) can be determined as $F_{max}^{mean} = 0.359$ kN, $\sigma = 81.40$ and COV = 0.23, respectively, see (4) to (6).

$$F_{max}^{mean} = (268 + 466 + 347 + 357)/4 = 359\ N \quad (4)$$

$$\sigma^2 = 1/3 \cdot [(268 - 359)^2 + (466 - 359)^2 + (347 - 359)^2 + (357 - 359)^2] \quad (5)$$
$$\sigma = 81.40$$

$$COV = \sigma / F_{max}^{mean} = 81{,}40/359 = 0.23 \quad (6)$$

Moreover the 5 % quantile can be calculated as $F_{max}^{5\%} = 0.280$ kN, see (7).

$$1 + (n-1) \cdot p = 1 + (4-1) \cdot 0.05 = 1.15$$
quantile is between the smallest (268 N) and second smallest (347 N) result (7)
$$F_{max}^{5\%} = 268 + (347 - 268) \cdot (1.15 - 1.00) = 280\ N$$

2.2 PULL-OUT TESTS

2.2.1 Set-up

In order to study the load-bearing behaviour of connections with beech dowels under tension forces, a modified pull-out test for fasteners has been applied, which enables one to assess the tension resistance of different arrangements of fasteners.

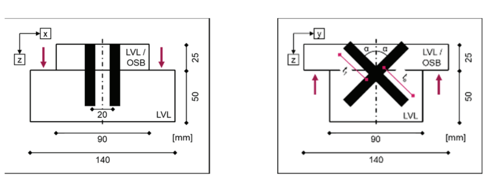

***Figure 1:** Pull-out test – Test set-up*

Each pull-out test contains two wooden specimens that are connected by a pair of dowels in various geometric positions. The set-up can be seen in Figure 1.

The load protocol is chosen according to EN 26891 [6]: firstly, an estimated failure loading needs to be selected. The initial loading level is set at 40 % of this estimated failure loading – the strain is increased until this level and then kept constant for 30 seconds. After that, the strain is released to 10 % of the estimated failure loading and then again kept constant at this level. Finally, the strain is increased until the specimen fails – the failure loading has been reached.

2.2.2 Parameters

Forty pull-out tests were conducted with laminated veneer lumber (LVL) and oriented strand board (OSB) to be connected with four different inclinations of the dowels.

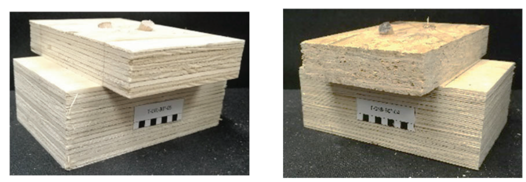

***Figure 2:** Pull-out test – Specimen, wood dowels, inclination 30°, left LVL/LVL, right OSB/LVL*

An LVL specimen with wood dowels arranged with an angle of $\alpha = 30°$ can be seen in Figure 2. Figure 3 shows the situation during manufacturing for $\alpha = 30°$.

***Figure 3:** Pull-out test – Detail, wood dowels, inclination 30° (pretesting)*

Variations considered

The test setting with vertically oriented dowels represents the most inappropriate case, where methodically, no forces straight orthogonally to the specimen surface can be transmitted. The pull-out resistance results because of friction between the specimen and the cylindrical surface of the dowels.

The second limit case considered occurs by tilting the dowels for $\alpha = 45°$. In this constellation, both vertical and horizonal forces are transmitted in addition to friction; moreover, tension and bending within dowels occur.

Intermediate tests with $\alpha = 15°$ and 30° were conducted to evaluate the influence of different angles.

Material and geometrical specifications

The bottom part of the specimens has a thickness of 50 mm and is always made of LVL. By contrast, the material of the upper layer is varied between LVL and

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OSB, both with a thickness of 25 mm. Additional data concerning the dimensions of the specimen can be found in Figure 1.
The fasteners are made of beech and have a corrugated cylindrical surface. The diameter is 10 mm, and the dowel holes are predrilled with a diameter of 9.5 mm. The penetration lengths can be calculated for the individual situation.

2.2.3 Results

The F-t diagram and the corresponding F-u diagram are illustrated for one particular variation – OSB/LVL, inclination 15° – in Figure 4. These curves are exemplary for the whole pull-out testing campaign.

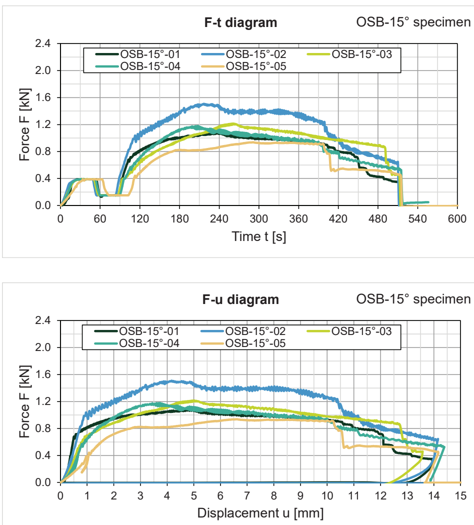

Figure 4: *Pull-out test – Exemplary test date*

All results which are presented in the following refer to “Two Fasteners in One Shear Plane with a Crossed (‘X’) Arrangement”. This note can be found in the upper right-hand corner of the diagrams.

Failure loading and failure mode

Results of the pull-out tests are displayed in Figure 5 and Figure 6. The diagrams show the maximal tension force as a function of the installation angle.

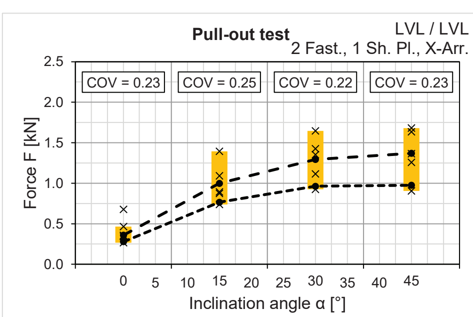

Figure 5: *Series 1 – Pull-out test – max Force – LVL/LVL*

One “0° test” is neglected in Figure 5, because of a faulty load protocol. Figure 6 shows that the maximal tension force fell below significantly for two of the five “0° tests”. They are also neglected.

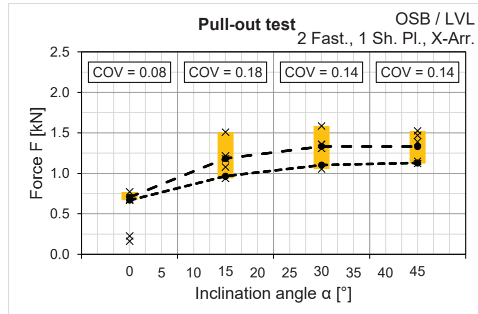

Figure 6: *Series 1 – Pull-out test – max Force – OSB/LVL*

The tension resistance rises considerably in relation to the vertical arrangement if the fasteners are tilted only about $\alpha = 15°$. Additional tilting improves the tension resistance in the following, but the increase is no longer as significant.
Both combinations considered – LVL/LVL and OSB/LVL – reach a similar level of failure loadings.

Slip modulus

In addition, the stiffnesses are also determined. Two different slip moduli (K_{init} and K_{re}) are determined corresponding to the specifications of the load protocol (initial load to 40 % of the estimated failure loading; relief to 10 % of the estimated failure loading; reload until the failure loading is reached). The gradient between 5 % and 35 % of the estimated failure loading is calculated for the initial slip modulus. The gradient in the force-displacement curve is determined between 10 % and 50 % of the failure loading to get the slip modulus of the reloading section.

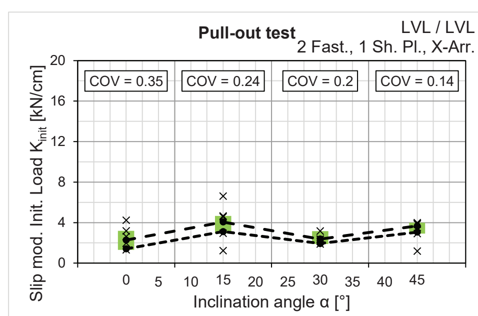

Figure 7: *Series 1 – Pull-out test – Slip modulus init. loading – LVL/LVL*

The results in Figure 7 to Figure 10 illustrate the particular slip moduli again as a function of the inclination angle. The style of the diagrams matches the ones already presented. Once more, the outliers are displayed as mentioned earlier, but are not considered for the further course of the discussion.

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As seen in Figure 7 and Figure 8, no clear correlation between the slip modulus and inclination angle can be found. While K_{init} can be recognised as constant for the LVL/LVL specimen, a nearly linear increasing graph can be found for the OSB/LVL tests.
Concerning the different material combinations, it can be assumed that the OSB variation leads to higher slip moduli in contrast to the LVL variation.

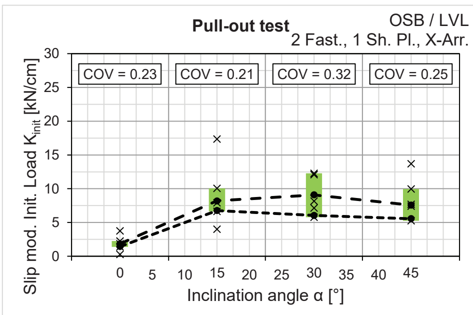

Figure 8: *Series 1 – Pull-out test – Slip modulus init. loading – OSB/LVL*

Figure 9 and Figure 10 show the slip moduli for the reloading section of the test series conducted. In this case, it can be seen even more clearly that no straight dependence occurs. The OSB/LVL tests in Figure 10 differ significantly due to the inclination angle.

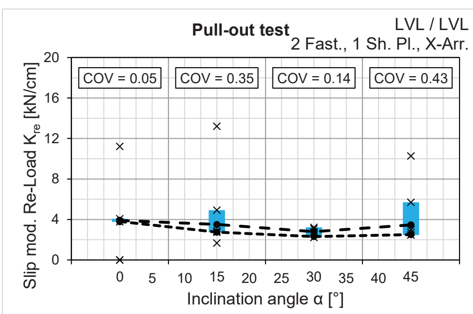

Figure 9: *Series 1 – Pull-out test – Slip modulus reloading – LVL/LVL*

Comparing the LVL and the OSB tests, higher slip moduli can again be determined for the latter.

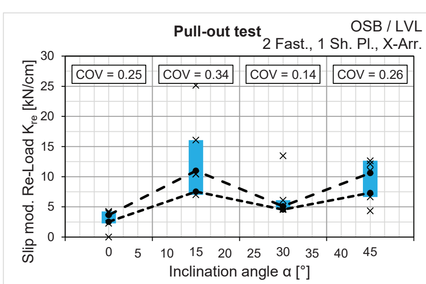

Figure 10: *Series 1 – Pull-out test – Slip modulus reloading – OSB/LVL*

2.3 SHEAR TESTS

2.3.1 Set-up

In order to evaluate the performance of the beech dowels under shear loading, several experimental tests were conducted. The test set-up is shown in Figure 11.

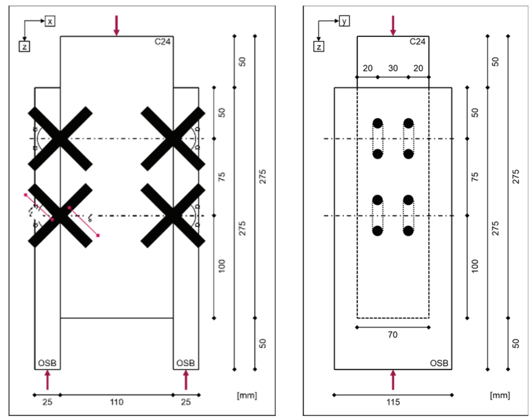

Figure 11: *Shear test – Test set-up*

Specimens with OSB elements and one C24 element are constructed for the investigations. The connection between the OSB panels and the C24 part is realised with eight wooden dowels. The fasteners are inclined with different angles, similar to those applied for the pull-out tests.
The middle parts have dimensions of 110 x 70 x 275 mm, while the panels are 25 x115 x 275 mm.
The load protocol is again chosen according to EN 26891 [6]. For more information, see 2.2.1.

2.3.2 Parameters

There are a total number of 20 shear tests in series 1. In terms of material specifications, only the combination of OSB panels with a C24 beam is considered. Again, four different angles are investigated.

Figure 12: *Shear test – Specimen and test set-up*

Figure 12 and Figure 13 show a specimen, the test set-up and some selected details.
Five tests are performed for each of the four different angles – α = 0°, 15° 30° and 45°.

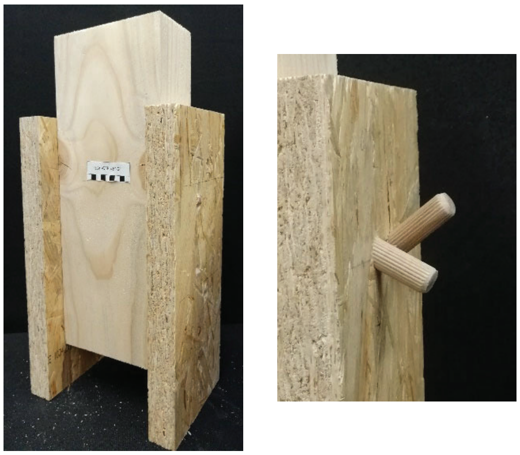

Figure 13: Shear test – Specimen, detail, wood dowels, inclination 45°

The diameter of the fasteners is again set at 10 mm, and the dowel holes are predrilled with a diameter of 9.5 mm. The penetration lengths correspond with the length of the fasteners of 70 mm and the particular set-up.
Details concerning the dimensions of the specimen can be found in 2.3.1.

2.3.3 Results

Figure 14 shows an example of the set-up with α = 15°; the values measured compiled as both an F-t and a F-u diagram. The current curves are valid for two fasteners with one shear plane.

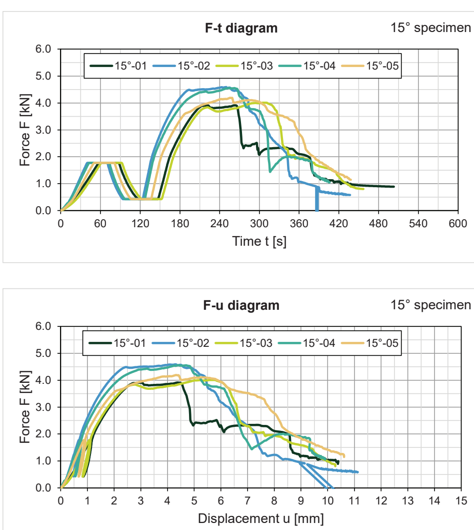

Figure 14: Series 1 – Shear test – Exemplary test results

All results presented in the further course refer to “Four Fasteners in Two Shear Planes with a Crossed (‘X’) Arrangement”. This note can be found in the upper right-hand corner of the diagrams.
See 2.2.3 for the style and layout of the results.

Failure loading and failure mode
The maximal loads as a function of the inclination angle can be seen in Figure 15. A rather clear correlation can be found. The maximum force decreases as the angle increases.

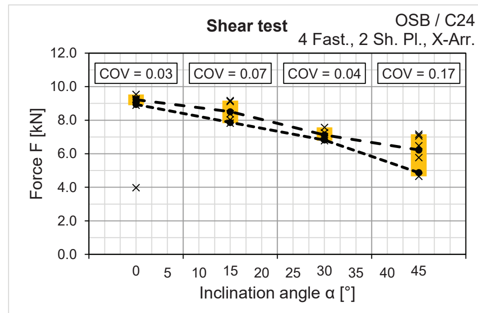

Figure 15: Series 1 – Shear test – max Force – OSB/C24

In this case, the cross-wise arrangement of the dowels – see detail in Figure 13 – indicates the course of the test results. Regarding α = 0°, each dowel is loaded in the same way, while for other angles, only one out of two dowels contribute to the load-bearing capacity.
Slip modulus

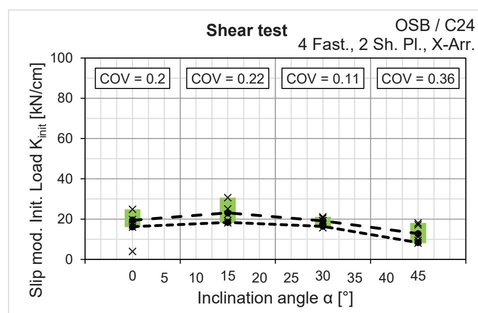

Figure 16: Series 1 – Shear test – Slip modulus init. loading – OSB/C24

In addition to the failure loadings, the slip moduli are also determined. The results – firstly, for the initial loading section, secondly, for the reloading section – can be found in the diagrams in Figure 16 and Figure 17.

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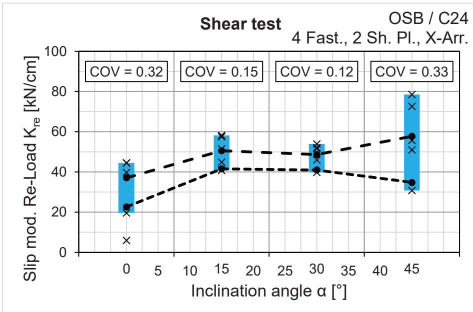

Figure 17: *Series 1 – Shear test – Slip modulus reloading – OSB/C24*

As the experimental results indicate, both slip moduli are more or less independent of the inclination angle. This may be due to the ambiguous effect of the different arrangements of the fasteners – on the one hand, tilting the dowels improves the load-bearing capacity, but, on the other hand, the pairwise opposing orientation reduces the load-bearing capacity.

While K_{init} slightly decreases with an increasing angle (Figure 16), K_{re} tends to increase in this course (Figure 17). The initial slip modulus is generally less than half of the slip modulus for the reloading.

3 TEST SERIES 2

3.1 GENERAL INFORMATION

The main focus in the second test series is on evaluating the influence of different penetration lengths of the dowels. As has already been conducted within test series 1, pull-out and shearing test are performed. This time, as a secondary parameter, the inclination angle is varied for only two values – pull-out tests are done for α = 15° and 30°, whereas shearing tests are conducted for α = 0° and 30°.

Five specimens were tested for each parameter combination. The material specifications are point, with OSB and C24 as materials for all investigations. A total of 30 pull-out and 30 shear tests were conducted.

The diameter ($d_{fastener}$ = 10 mm) of the wooden dowels constant, while the particular length for test series 2 corresponds with the penetration length of each set-up.

3.2 PULL-OUT TESTS

3.2.1 Set-up

The set-up for the pull-out test in the second test series complies with that in series 1. Details can be found in 2.2.1.

Similar to the first test series, the dimensions of the specimens are 90 x 140 x 50 mm for the lower element (C24) and 140 x 90 x 25 mm for the upper element (OSB).

3.2.2 Parameters

The penetration length in the lower timber element (C24) is given in relation to the thickness of the upper timber element (OSB). With t_1 = 25 mm and t_e / t_1 = 1.0, 1.5 and 2.0, the particular values are t_e = 25.0, 37.5 and 50.0 mm. The total length of the fasteners are $\ell_{fastener}$ = 50.0, 62.5 and 75.0 mm.

3.2.3 Results

Due to the corresponding testing conditions, the remarks given in 2.2.3 hold as well.

Failure loading and failure mode

The results of the experimental tests are illustrated in Figure 18. Here, the diagrams show the maximum force over the penetration length.

It can be seen that the penetration length has no significant influence on the failure loading. A clear effect cannot be found because of the statistical deviation. As a trend, it can be assumed that the rising penetration length leads to a higher failure loading.

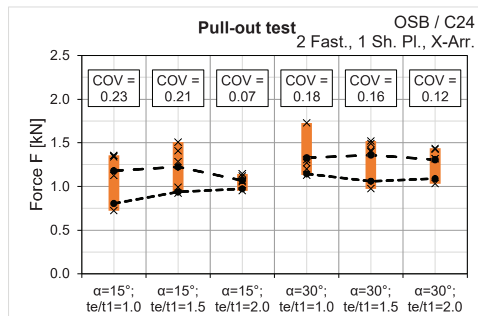

Figure 18: *Series 2 – Pull-out test – max Force – OSB/C24*

Slip modulus

In addition, the two slip moduli discussed already are also determined. Figure 19 and Figure 20 show the corresponding results.

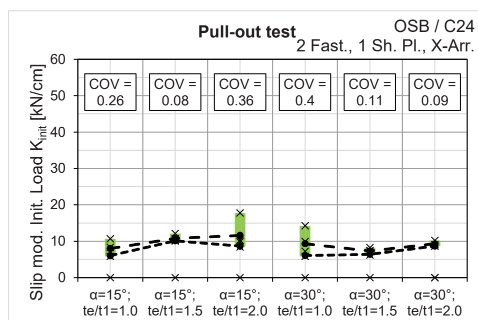

Figure 19: *Series 2 – Pull-out test – Slip modulus init. loading – OSB/C24*

Regarding the initial load section, the slip modulus is almost constant and, thus, not influenced by the penetration length (see Figure 19).

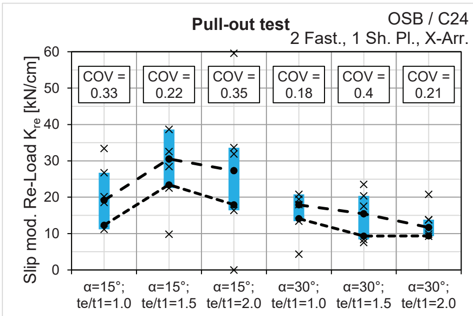

Figure 20: *Series 2 – Pull-out test – Slip modulus reloading – OSB/C24*

By contrast, although the slip modulus for the reloading section (see Figure 20) is obviously affected by the penetration length, a direct correlation cannot be found.

3.3 SHEAR TESTS

3.3.1 Set-up

The test set-up for the shear tests of the second test series is the same as test series 1. Further information can be found in 2.3.1.

3.3.2 Parameters

The main focus of the pull-out tests presented previously is on the influence of different penetration lengths. The particular lengths investigated are $t_e = 25.0$, 37.5 and 50.0 mm. Moreover, two inclination angles are considered: $\alpha = 0°$ and 30°.

3.3.3 Results

See 2.3.3 for the layout and more details about the following diagrams.

Failure loading and failure mode

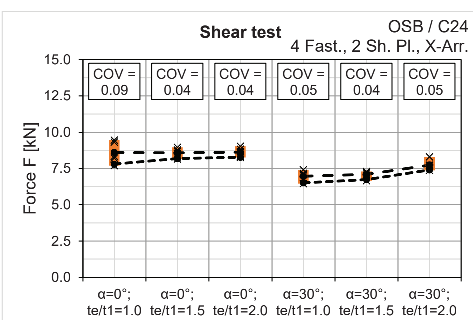

Figure 21: *Series 2 – Shear test – max Force – OSB/C24*

Figure 21 contains the maximal failure loadings determined experimentally for the different set-ups considered. It can be seen that there is only a slight effect of the penetration length. Regarding the inclination angle, the results presented show a decreasing trend when increasing the tilting.

Slip modulus

Figure 22 and Figure 23 show the slip moduli which are determined for the initial and the reloading section. The results indicate that at least K_{init} is not significantly influenced by the penetration lengths. No clear trend is obvious.

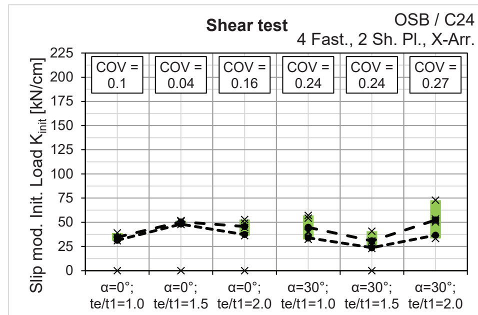

Figure 22: *Series 2 – Shear test – Slip modulus init. loading – OSB/C24*

Concerning K_{re}, on the one hand, there seems to be a corresponding correlation for $\alpha = 0°$, however, on the other hand, no clear effect can be proved for $\alpha = 30°$.

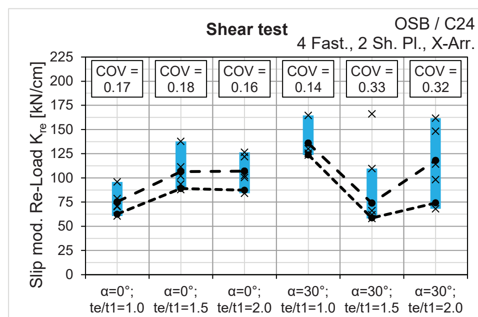

Figure 23: *Series 2 – Shear test – Slip modulus reloading – OSB/C24*

4 DISCUSSION AND INTERPRETATION

4.1 PULL-OUT TESTS

The results of the pull-out tests are summarised in Table 2, Table 3 and Table 4; the tables contain the mean value and the 5 % quantile of each particular configuration. Normal distribution was assumed and the quantiles have been calculated as given in (7).

Table 2: *Pull-out test – max Force*

Configuration			*n [-]*	*F [kN]* mean value	*F [kN]* 5 % quantile
Series 1	LVL/LVL	α=0°	4	0.359	0.280
		α=15°	5	0.999	0.765
		α=30°	5	1.294	0.964
		α=45°	5	1.370	0.976

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	OSB/LVL		α=0°	3	0.705	0.669
			α=15°	5	1.184	0.966
			α=30°	5	1.333	1.104
			α=45°	5	1.332	1.128
Series 2	OSB/C24	t_e/t_1 1.0	α=15°	5	1.180	0.805
			α=30°	5	1.227	1.141
		1.5	α=15°	5	1.224	0.937
			α=30°	5	1.360	1.060
		2.0	α=15°	5	1.068	0.973
			α=30°	5	1.306	1.090

Comparing the results of both test series, it can be outlined that the failure loadings in series 2 fit in well to the ones of series 1. The increase of the inclination angle leads to a higher load-bearing capacity, whereby the effect flattens with increasing angles. Table 2 indicates that a clear effect of the different material combinations cannot be found. Thereby, the failure of the specimen seems to be caused by the fasteners themselves.

Table 3: *Pull-out test – Slip modulus init. loading*

Configuration				*n [-]*	*K_{init} [kN/cm]* mean value	5 % quantile
Series 1	LVL/LVL		α=0°	4	2.28	1.42
			α=15°	3	4.02	3.12
			α=30°	5	2.38	1.94
			α=45°	4	3.68	3.06
	OSB/LVL		α=0°	3	1.84	1.45
			α=15°	4	8.21	6.78
			α=30°	5	9.10	6.07
			α=45°	4	7.59	5.58
Series 2	OSB/C24	t_e/t_1 1.0	α=15°	4	7.98	6.04
			α=30°	4	9.32	6.07
		1.5	α=15°	4	10.78	10.11
			α=30°	4	7.31	6.39
		2.0	α=15°	4	11.58	8.64
			α=30°	3	9.29	8.66

By contrast, it can be detected that the two slip moduli and, with it, the deformation of the specimen, are influenced by the different materials. Table 3 and Table 4 show that the slip moduli of the LVL tests are lower than the other ones for most configurations. The results of series 2 especially indicate that the material combination has a large impact on the performance.

Table 4: *Pull-out test – Slip modulus reloading*

Configuration				*n [-]*	*K_{re} [kN/cm]* mean value	5 % quantile
Series 1	LVL/LVL		α=0°	2	3.92	3.79
			α=15°	3	3.51	2.76
			α=30°	5	2.80	2.32
			α=45°	4	3.47	2.51
	OSB/LVL		α=0°	4	3.66	2.53
			α=15°	4	11.01	7.53
			α=30°	4	5.12	4.58
			α=45°	4	10.62	7.62
Series 2	OSB/C24	t_e/t_1 1.0	α=15°	4	19.17	12.31
			α=30°	4	17.92	14.10
		1.5	α=15°	4	30.53	23.41
			α=30°	3	15.45	9.32
		2.0	α=15°	3	27.30	17.94
			α=30°	4	11.68	9.37

4.2 SHEAR TESTS

Table 5, Table 6 and Table 7 summarise the results of the shear tests of both series. The mean values determined and the corresponding quantiles are given for each configuration.

Table 5: *Shear test – max Force*

Configuration				*n [-]*	*F [kN]* mean value	5 % quantile
Series 1	OSB/C24		α=0°	4	9.232	8.942
			α=15°	5	8.504	7.864
			α=30°	5	7.119	6.819
			α=45°	5	6.227	4.877
Series 2	OSB/C24	t_e/t_1 1.0	α=0°	5	8.600	7.796
			α=30°	5	6.964	6.508
		1.5	α=0°	5	8.574	8.177
			α=30°	5	7.083	6.733
		2.0	α=0°	5	8.618	8.269
			α=30°	5	7.729	7.396

On the one hand, it can be seen that the results of both test series for the failure loadings (Table 5) are very close.

Table 6: *Shear test – Slip modulus init. loading*

Configuration				*n [-]*	*K_{init} [kN/cm]* mean value	5 % quantile
Series 1	OSB/C24		α=0°	4	19.50	16.21
			α=15°	5	23.11	18.38
			α=30°	5	19.15	16.41
			α=45°	5	12.81	8.36
			α=0°	4	34.52	31.40

				α=30°	5	44.74	33.83
			1.5	α=0°	4	50.37	48.18
				α=30°	4	30.74	23.74
			2.0	α=0°	4	45.65	37.40
				α=30°	5	52.33	36.63

Table 7: *Shear test – Slip modulus reloading*

Configuration					*n [-]*	*K_{re} [kN/cm]* mean value	*K_{re} [kN/cm]* 5 % quantile
Series 1	OSB/C24			α=0°	4	37.09	22.62
				α=15°	5	50.57	41.57
				α=30°	5	48.69	41.00
				α=45°	5	57.73	34.82
Series 2	OSB/C24	t_e/t_1	1.0	α=0°	5	75.26	62.58
				α=30°	4	135.96	123.90
			1.5	α=0°	5	106.54	89.03
				α=30°	4	74.00	58.62
			2.0	α=0°	5	107.06	87.33
				α=30°	5	118.16	74.16

Due to the slip moduli, on the other hand, the results indicate a significant deviation between the two test series. In this context, it has to be emphasised that the evaluation of the data is of great importance. The particular way of determining the gradients (initial and reloading section) of the load-displacement curves must be considered.

In addition, the effect of the different penetration lengths shows no clear tendency. More testing with other specifications is necessary in order to evaluate this effect.

5 CONCLUSIONS AND OUTLOOK

The results presented lead to a better understanding of connections with wood dowels under tension and shear. Wood dowels are easy to use, flexible, sustainable and represent a promising alternative not only in the restoration sector but also for new constructions.

More investigations concerning doweled connections under shear and tension will be carried out to understand the load-bearing behaviour of these fasteners and, thus, to expand the application area.

As an additional approach, other geometrical and material specifications – different diameters, wider range of penetration lengths, alternative arrangements of the fasteners – will be investigated.

As a consequence of the research approach, further application areas for wooden dowels and similar fasteners should be found. This will lead to a more sustainable and appropriate use of wooden construction elements.

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