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MOISTURE AND ASSEMBLY HISTORY EFFECTS ON EMBEDMENT PROPERTIES OF STEEL DOWELS IN SPRUCE AND BIRCH LOADED IN GRAIN DIRECTION

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ABSTRACT: Embedment strength and stiffness of steel dowels in spruce and birch solid wood were investigated in an experimental study, taking into account the moisture and connection assembly history. Thus, in addition to the effect of different mechanical properties of wood at different moisture contents, the effect of changes in the moisture content between the steps of: drilling the dowel hole, assembly of the dowel, and testing of the specimen on the embedment strength and stiffness was studied. Full-hole embedment tests with 12 mm steel dowels showed a decrease in embedment strength with increasing wood moisture content, while the elastic embedment stiffness was not influenced. Drying the wood specimens after the dowel was inserted yielded up to 50% higher elastic embedment stiffness compared with connections drilled and assembled when the equilibrium moisture content was reached. Application of an artificial crack showed only a moderate effect on embedment strength and stiffness, while the ductile embedment behavior was maintained.

KEYWORDS: Embedment strength and stiffness, experiments, spruce, birch, moisture content, assembly history

1 INTRODUCTION

Structural timber elements undergo from their production, over drilling boreholes for the fasteners, transportation, to the joint assembly, as well as during the service life, multiple changes in the ambient climate (temperature and relative humidity). This results in changes of the moisture content (MC) in the joint area, which influences the mechanical properties of the wood and thus the mechanical behavior of the joint. In addition, variations in MC lead to geometrical changes of the timber around the steel dowels by means of shrinkage and swelling, while the geometrical shape of the steel dowel itself is unaffected. This can lead to moisture induced pre-stressing of the wood matrix around the dowel, or to shrinkage cracks when the tensile strength of the wood perpendicular to the grain is exceeded.

The embedment strength is the parameter, which represents the mechanical response of wood loaded by a dowel-type fastener in the European Yield Model. The latter is used for the calculation of the capacity of a single-fastener connection according to Eurocode 5 [6]. A possibly reduced capacity due to an increased MC (and the load duration) is considered by multiplication of the characteristic connection capacity with the modification factor, k_{mod}, when calculating a design capacity of a connection. For service class 3, the embedment strength is thus indirectly decreased due to the higher MC, while no reduction due to MC is considered for service classes 1 and 2 [6]. This is however in contradiction to findings from [1]-[4], who found a decreased embedment strength, f_h, for increasing MCs within service classes 1 and 2. Hardly investigated is the influence of the MC on the embedment stiffness, k_{el} (e.g. [4]). In the studies [1]-[4], test specimens were produced after the targeted equilibrium MC was reached, and thus the history of moisture changes was not considered. In contrast, Sjödin et al. [5] conducted an experimental study to investigate the influence of a decreasing MC after assembly of a multi-dowel steel-to-timber connection on the connection capacity, while the connection stiffness was not studied. A decrease in connection capacity with decreasing MC was found, which was explained by moisture gradient induced stresses, initiating small cracks in the connection area. However, to the best of our knowledge such a study was not yet carried-out on the embedment level.

In this contribution, the aim is to investigate the influence of the moisture and assembly history on the embedment strength and stiffness in grain direction by means of an experimental study. Thus, not only the influence of the MC on the embedment properties, but also the influence of different MCs in combination with the manufacturing and assembly history: drilling of the dowel hole, assembly of the dowel, and embedment testing, including even the influence of a crack underneath the dowel-wood interface, is investigated.

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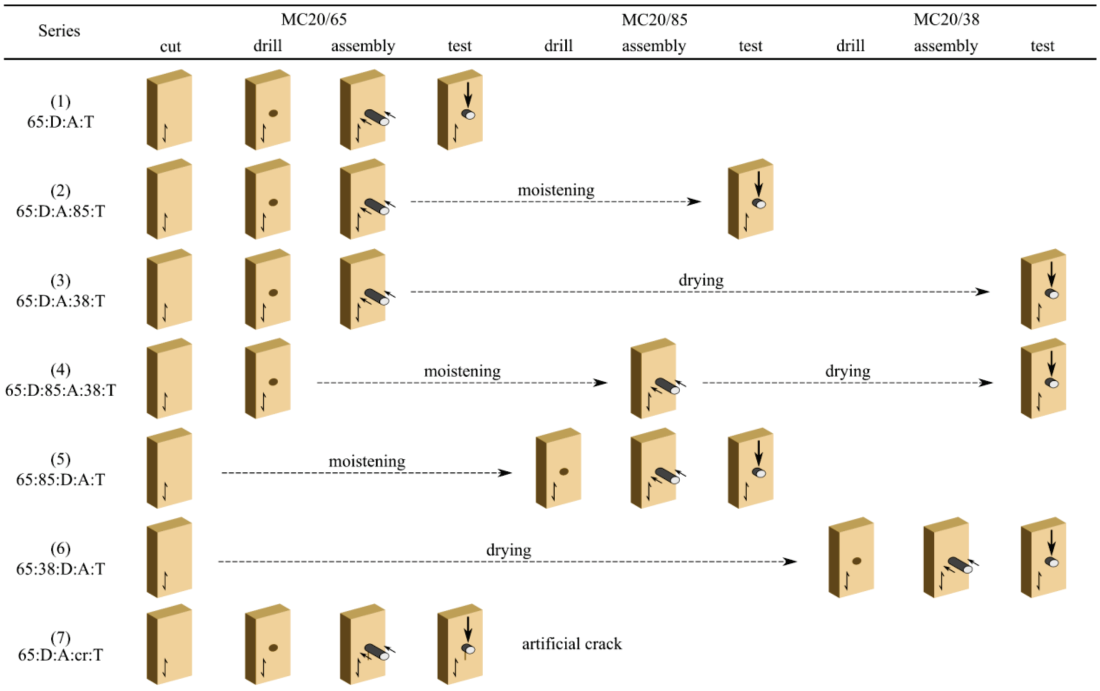

Figure 1: *Embedment test series for spruce and birch, indicating the ambient climate at: specimen cutting (cut), dowel hole drilling (drill), dowel assembly (assembly) and testing (test). Note: D…drill, A…assembly, cr…artificial crack, T…test, 38, 65, 85…corresponding relative humidity in (%).*

2 MATERIAL AND METHODS

2.1 Experimental program and materials

To study the influence of the moisture and assembly history on the embedment strength and stiffness in grain direction, seven groups of ten spruce and birch specimens each, with similar density distribution, were created (Figure 1). These groups differed by the moisture content (MC) of the specimen at the time: the dowel hole was drilled, the dowel was inserted, and the specimen was tested. In total, three different MCs, corresponding to ambient climates of 20°C and 65% RH (MC20/65 as a standard climate condition for testing), 20°C and 85% RH (MC20/85 as a condition with a higher MC), and 20°C and 38% RH (MC20/38 as a condition with lower MC) were used in the experimental program. These three ambient climates could be seen as representative for service class 1-3 in the current European design standard for timber structures, Eurocode 5 [6].

Series (1) served as a reference series, at which drilling, assembly and testing were done at the same MC, i.e. MC20/65 (standard climate condition for testing). The same procedure was followed for Series (5) and (6), but at a condition with high MC (MC20/85), and low MC (MC20/38), respectively. For Series (2) and (3), drilling and assembly were done at the reference condition (MC20/65), while testing was carried out in high MC (MC20/85) and low MC (MC20/38) conditions. Series (4) represents the situation of drilling right after production (MC20/65), assembly on-site after exposure to rain (MC20/85), and subsequent indoor application (testing at (MC20/38)). In addition, Series (7) investigates a damaged state, by application of an artificial crack parallel to the grain underneath the dowel-wood interface and aligned with the dowel hole center (see Figure 1), at MC20/65.

In total, 140 tests were conducted, uniformly distributed over seven different test series, with ten tests each, and two wood species, namely spruce and birch. Embedment test specimens were produced out of solid timber boards according to the corresponding European test standard, EN 383 [7]. Systematic selection of the specimens allowed for similar mean density and similar density distribution in the seven test series (Table 1). This was achieved by sourcing specimens from ten different boards, where each board provided one specimen per test series. The careful specimen selection was of importance in order to avoid large variations in wood characteristics that could influence the embedment properties. More details about the specimen sourcing are given in [8].

The mean density at an ambient climate of 20°C and 65% RH, amounted to 468.4 kg/m^3 (CV= 10.0%) for spruce, and 623.2 kg/m^3 (CV= 5.6%) for birch. The mean moisture content (MC) of the specimens at the time of testing is given per test series and species in Table 1. For determination of the MC, the oven-dry method according to EN 13183-1 [9] was used by placing the specimens in an oven at 103 ± 2°C directly after the embedment test. An ambient climate of 20°C and 65% RH resulted in a mean MC of 13.7% (CV= 2.7%) for spruce, and 11.0% (CV= 3.2%) for birch, while an ambient climate of 20°C and 85% RH resulted in a mean MC of 16.6% (CV= 1.2%) for spruce, and 14.9% (CV= 1.8%) for birch. An ambient climate of 20°C and 38% RH resulted in a mean MC of 8.6% (CV= 2.1%) for spruce, and 7.8% (CV= 2.6%) for birch.

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Table 1: *Mean density at 20°C and 65% RH, ρ, (kg/m³), and mean moisture content at testing, MC, (%), and their coefficient of variation, CV, (%) of spruce and birch specimens.*

Series	ρ (kg/m³) Mean | CV (%)	*MC* (%) Mean | CV (%)
Spruce		
(1) 65:D:A:T	467.7 | 9.9%	14.0 | 2.0%
(2) 65:D:A:85:T	464.7 | 9.6%	16.7 | 1.2%
(3) 65:D:A:38:T	464.7 | 10.2%	8.8 | 0.7%
(4) 65:D:85:A:38:T	473.6 | 9.6%	8.5 | 1.4%
(5) 65:85:D:A:T	468.5 | 10.5%	16.6 | 1.2%
(6) 65:38:D:A:T	472.1 | 9.2%	8.4 | 1.1%
(7) 65:D:A:cr:T	467.5 | 10.6%	13.5 | 2.1%
All specimens	468.4 | 10.0%	
Birch		
(1) 65:D:A:T	624.4 | 5.1%	10.8 | 3.1%
(2) 65:D:A:85:T	625.0 | 6.6%	14.9 | 2.0%
(3) 65:D:A:38:T	618.8 | 5.1%	8.0 | 1.4%
(4) 65:D:85:A:38:T	627.2 | 5.8%	7.7 | 1.5%
(5) 65:85:D:A:T	625.4 | 6.4%	14.9 | 1.6%
(6) 65:38:D:A:T	623.3 | 5.0%	7.6 | 1.8%
(7) 65:D:A:cr:T	618.4 | 5.1%	11.1 | 2.6%
All specimens	623.2 | 5.6%	

Note: D…drill, A…assembly, cr…artificial crack, T…test, 38, 65, 85…corresponding relative humidity in (%)

Specimen dimensions followed the rules of EN 383. Thus, for a dowel with a diameter of *d*=12 mm, loaded in grain direction, the specimen height, *h*, (in grain direction) was 168 mm (twice 7*d*), the width, *w*, was 72 mm (twice 3*d*), and the thickness, *t*, was chosen to 36 mm (3*d*). All boards were stored in a climate chamber at an ambient environment of 20°C and 65% RH until the equilibrium moisture content was reached. Thereafter, the specimens for all test series were cut, and further processed according to the test program given in Figure 1. Equilibrium moisture content was assumed to be reached when two successive weightings, at an interval of 24 h, did not differ by more than 0.1% of the specimen mass, which is stricter than the rule given in EN 383 [7].

Immediately before testing, all specimens were reinforced with two partly-threaded screws (*d*=6 mm), to avoid early brittle failure of the specimen, i.e. before the targeted maximum embedment displacement of 15 mm was reached, as it was seen e.g. in [1] and [3]. Two screws, one above and one below the dowel were inserted at a distance of 36.5 mm from the dowel axis (Figure 2). The distance was decided based on results from Lederer et al. [10], to allow for a minimum distance between dowel and screw of one time the dowel diameter, i.e. 12 mm, at the end of the test. Thus, ductile behavior is ensured while a strength increase by the reinforcement screw is avoided. Moreover, this distance is far enough to not affect the elastic behavior of the wood-to-dowel contact.

Depending on the test series, the electrogalvanized dowel of steel quality S235, with *d*=12 mm was inserted either before the moisture content in the wood was adjusted or directly before testing. The borehole for the dowel was drilled to 12 mm in diameter without any clearance.

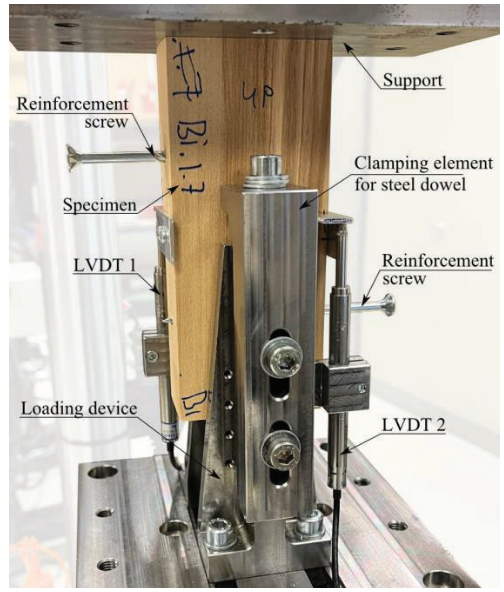

Figure 2: *Embedment setup for loading in grain direction according to EN 383 [7], including reinforcement screws to avoid premature splitting and 2 LVDTs for local displacement measurement.*

An artificial crack below the dowel with a length of 15 mm and a width of 0.5 mm, over the full specimen depth was added for Series (7). For this purpose, a small precision band saw was used. For more details, the reader is referred to [8].

2.2 Test setup and loading protocol

Full-hole embedment tests according to EN 383 [7], of 12 mm steel dowels embedded in spruce and birch specimens, loaded in grain direction were carried-out. The specimens were placed in a uniaxial testing machine (MTS 810, MTS Systems Corporation), by clamping both dowel ends in the loading device (Figure 2). Clamping of the dowel was used to minimize the effect of elastic bending of the dowel to ensure a uniform load transfer to the timber specimen along the dowel. A gap of 1 mm at each side between specimen and loading device was ensured to avoid friction between these elements.

On each side of the test setup, one displacement transducer (LVDT) was attached to measure the relative local displacement, *u*, between specimen and the loading device, and thus between the dowel and the timber specimen. For this purpose, steel angle brackets were diagonally mounted on the timber specimen's sides, in line with the dowel, to act as counterparts for the LVDTs mounted to the loading device. The force, *F*, as a result of embedment loading was directly measured by the load cell of the machine. In addition, the displacement of the actuator giving the machine displacement, u_{MTS}, was recorded.

The loading procedure followed the regulations of EN 383 [7], with small modifications. Loading was applied in grain direction until a machine displacement, u_{MTS}, of 17 mm, to ensure a local embedment displacement, *u*, of at least 15 mm.

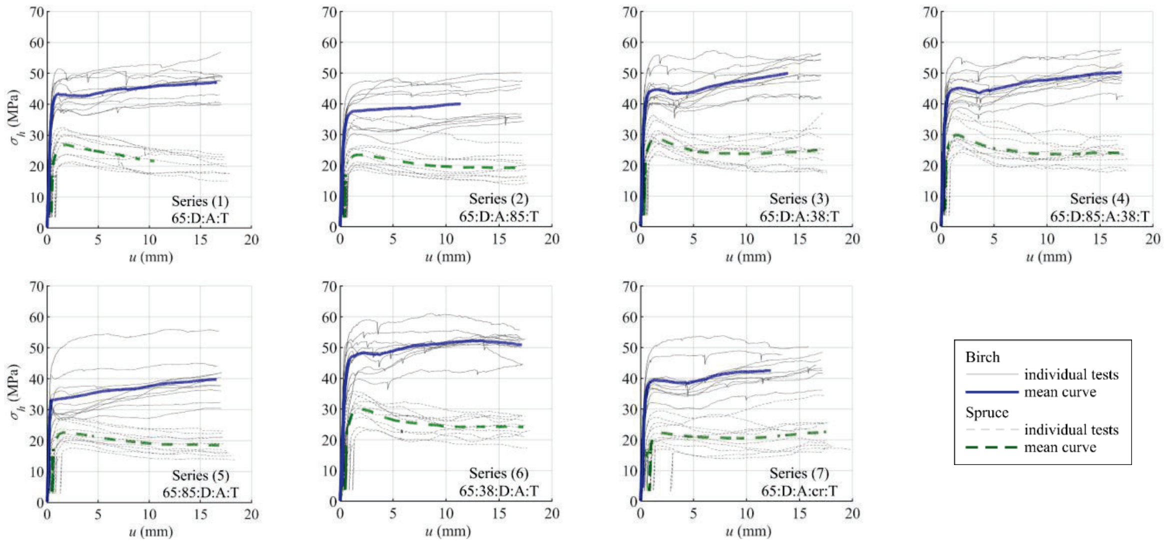

Figure 3: *Embedment stress-displacement curves for Series (1)-(7) of spruce (dashed lines) and birch specimens (continues lines).*

The displacement limit was increased compared to the 5 mm limit in EN 383 [7], to give access to the embedment behavior after yielding to serve as input for numerical models. The specimen was loaded force-controlled until a load level of 50% of the estimated maximum force, F_{est}, within 150 sec. This was followed by a 30 sec holding phase before the specimen was unloaded force-controlled with the same force rate to a force level of 10% of F_{est}. After a 30 sec holding phase, the specimen was re-loaded displacement-controlled with a displacement rate of 1.2 mm/min until u_{MTS} reached 17 mm.

2.3 Test evaluation

The local displacement, u, was determined as the average displacement measured by the two LVDTs. The embedment stress, σ_h, was calculated as the measured force, F, divided by the nominal contact surface of the dowel, i.e. the dowel diameter, d, times the specimen thickness, t. This gives access to the embedment stress-displacement curve for each test, from which the mean curve was determined by taking the average over the ten experiments per series.

The embedment strength, f_h, was defined according to EN 383 [7] as the maximum embedment stress up to a local displacement, u, of 5 mm. The elastic embedment stiffness, k_{el}, was defined as the inclination of the line, resulting from linear regression of the embedment stress-displacement curve between 10% and 40% of f_h as suggested in [8].

3 RESULTS AND DISCUSSION

3.1 Embedment stress-displacement curves

Embedment tests showed a pronounced global ductile behavior until the final displacement of more than 15 mm, thanks to the applied reinforcement screws. Most of the experiments showed local cracks in the wood below the dowel-wood contact surface, which however did not lead to global splitting of the specimen, as cracks were stopped at the reinforcement. These local cracks can be seen by load drops in the embedment stress-displacement curves illustrated in Figure 3. However, it also can be seen, that the force recovered after the crack-initiated load drop, reaching the load level before cracking.

Embedment stress-displacement curves for all seven test series, for both wood species (spruce and birch) are illustrated in Figure 3. Thin gray lines represent the individual tests, while thick green and blue lines give the mean curves of the individual test series per wood species. As typical for the embedment behavior of wood in grain direction, an almost linear behavior, representing the elastic range was observed for the first loading part. As soon as the elastic limit is reached, the stiffness decreases. For most of the tests, a local maximum is seen at this transition between elastic and plastic curve part, which is confirmed by previous tests [4,10,11]. Interestingly, spruce showed for most of the tests a continuous decrease in the embedment stress with increasing displacement, while the opposite was seen for birch, i.e., an embedment stress increase after the local maximum (see Figure 3). As expected, substantially higher embedment resistance was seen for birch compared to spruce, which confirms the correlation of the embedment resistance with the wood density [12,13].

3.2 Embedment strength and elastic stiffness

The embedment strength, f_h, as defined by EN 383 [7] (see Section 2.3), is given for Series (1)-(7) for both wood species, by its mean value and corresponding coefficient of variation (CV in %), in Table 2. For spruce specimens, a mean embedment strength, f_h, of 22.77 MPa to 30.34 MPa was found. The CV amounted to values below 20.5%. Birch specimens showed an f_h of 36.24 MPa to 49.24 MPa, with a CV of less than 19.9%. The difference in the mean embedment strength reflects the difference in MC between the test series. The about 60% higher embedment strength for birch compared to spruce is based

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Table 2: *Mean embedment strength, f_h, (MPa), and mean elastic embedment stiffness, k_{el}, (MPa/mm), and their coefficient of variation, CV, (%) of spruce and birch specimens.*

Series	f_h (MPa) Mean | CV (%)	k_{el} (MPa/mm) Mean | CV (%)
Spruce		
(1) 65:D:A:T	27.00 | 14.9%	49.44 | 26.5%
(2) 65:D:A:85:T	23.63 | 20.5%	51.09 | 29.7%
(3) 65:D:A:38:T	29.33 | 13.2%	72.80 | 27.1%
(4) 65:D:85:A:38:T	30.00 | 15.4%	73.29 | 32.6%
(5) 65:85:D:A:T	22.77 | 14.7%	48.88 | 44.4%
(6) 65:38:D:A:T	30.34 | 13.8%	48.85 | 37.7%
(7) 65:D:A:cr:T	22.79 | 17.6%	40.18 | 30.8%
Birch		
(1) 65:D:A:T	44.48 | 10.7%	104.81 | 16.5%
(2) 65:D:A:85:T	39.45 | 16.7%	103.76 | 15.2%
(3) 65:D:A:38:T	45.24 | 11.3%	133.53 | 20.0%
(4) 65:D:85:A:38:T	45.81 | 10.7%	121.45 | 19.0%
(5) 65:85:D:A:T	36.24 | 19.9%	113.83 | 19.3%
(6) 65:38:D:A:T	49.24 | 10.7%	112.07 | 31.5%
(7) 65:D:A:cr:T	39.97 | 14.7%	89.40 | 15.2%

Note: D…drill, A…assembly, cr…artificial crack, T…test, 38, 65, 85…corresponding relative humidity in (%)

on its higher density, even if the magnitude in f_h-difference cannot fully be explained by the density difference, which was only about 30%. One explanation could be the untypical low f_h-results measured for spruce for its corresponding density. Furthermore, different correlations between f_h and density might be applicable for softwoods (e.g. spruce) and hardwoods (e.g. birch) as it was proposed by Ehlbeck and Werner [12].

The elastic embedment stiffness, k_{el}, as defined in Section 2.3, is given for all test series in Table 2. For spruce, a mean elastic stiffness, k_{el}, of 40.18 to 73.29 MPa/mm was found. The CV amounted to values up to 44.4%. Birch specimens showed a k_{el} of 89.40 to 133.52 MPa/mm, with a CV of up to 31.5%. Interestingly, birch specimens showed consistently lower variation in k_{el}-results compared to spruce specimens, while in general the variation for the embedment stiffness was higher than for the embedment strength. This confirms the sensitivity in measuring embedment stiffness, as it was already seen in previous studies [4,11], resulting among others from inaccuracies of the specimen preparation, dowel hole drilling, test setup, and displacement measurement. Birch specimens showed an elastic stiffness, k_{el}, of about twice the stiffness of spruce. This indicates a considerably stronger increase of the elastic stiffness with increasing density as it was found in [13].

3.3 Influence of moisture content

Results form Series (1), (5) and (6), are compared to study the influence of the moisture content (MC) on the embedment behavior, embedment strength, f_h, and elastic embedment stiffness, k_{el}. In these test series, the steps of (i) drilling the dowel hole, (ii) assembly of the dowel, and (iii) testing, were carried out after the equilibrium moisture content was reached. Thus, the only difference between these test series is their MC, while the assembly history and average specimen density was the same for all series. Series (1) corresponds to the standard climate of 20°C and 65% RH (MC20/65), Series (5) to a condition of a higher MC at 20°C and 85% RH (MC20/85), and Series (6) to a condition with a lower MC at 20°C and 38% RH (MC20/38). Corresponding MCs are given in Table 1.

The embedment stress-displacement curves in Figure 4(a) show a clear difference in the embedment resistance when reaching the yield limit. Higher embedment stresses can be reached, the lower the MC of the wood specimen is. Similar curve shapes can be seen for the different MCs, while distinct differences are found in the curve shape between spruce and birch, as discussed in Section 3.1.

The embedment strengths, f_h, presented in Figure 4(b) reflect the increase of resistance with decreasing MC. Series (5) (MC20/85), showed a decrease in the average f_h of about 15% (spruce) and 19% (birch) compared to the reference MC (MC20/65) in Series (1). This corresponds to a decrease in f_h by 5.8% (spruce) and 4.6% (birch) per 1% decrease in MC. Series (6) (MC20/38), showed an increase in the average f_h of 11% (spruce and birch) compared to the reference MC in Series (1). This corresponds to an increase in f_h by 2.0% (spruce) and 3.4% (birch) per 1% decrease in MC. Thus, results from this study suggest a nonlinear correlation of the embedment strength, f_h, with the corresponding wood MC, as well as differences between the two investigated wood species. Nevertheless, values are overall in line with findings from Hübner et al. [3], Sandhaas et al. [2] and van Blokland et al. [4], who found a strength increase of 3-4%, 2%, and 4-7% per 1% MC increase, respectively.

The elastic embedment stiffness, k_{el}, is illustrated in Figure 4(c). Interestingly, neither spruce, nor birch showed a distinct correlation of k_{el} with the corresponding MC. The difference in the average stiffness between Series (1), (5) and (6) were lower than 2% (spruce) and 8% (birch). Results need to be interpreted with care, since the stiffness parameter, k_{el}, showed for most of the test series a considerable variation in the results. These results are to some extend in contradiction to findings from van Blokland et al. [4], who found a significant influence of the MC on the elastic embedment stiffness for the first loading sequence, while almost no influence was seen for the following unloading/reloading sequence.

3.4 Influence of assembly history

Results from Series (2) and (5) are compared in Figure 5 to study the influence of the assembly history at a higher moisture content MC, i.e., at a MC corresponding to an ambient climate of 20°C and 85% RH (MC20/85). The influence of the assembly history at lower MC (MC20/38) is studied by comparing Series (3), (4) and (6) in Figure 6. In series (5) and (6), respectively, the steps of drilling, assembly and testing were done after the equilibrium moisture content was reached, and thus could be seen as reference cases. In contrast, in Series (2) and (3), respectively, the steps of drilling and assembly were done before the MC was adjusted. Furthermore, in Series (4) drilling was done at MC20/65, assembly at MC20/85, and testing at MC20/38. Thus, the only difference between

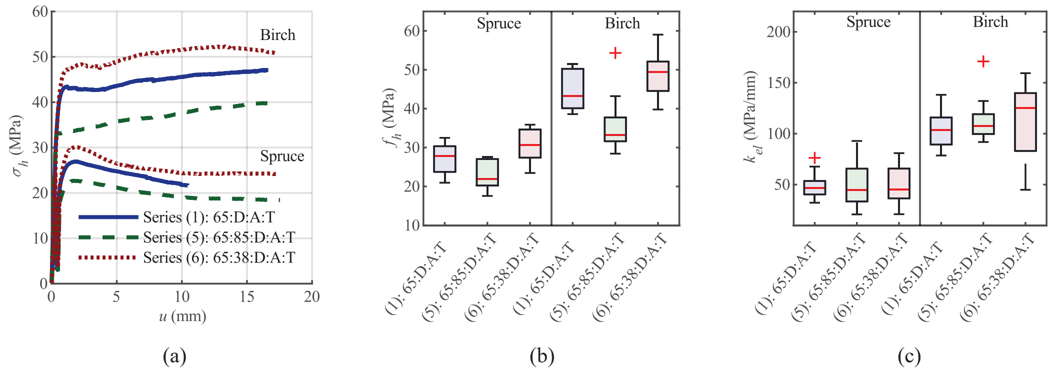

Figure 4: *Influence of the moisture content, MC, on (a) embedment stress-displacement curve, (b) embedment strength, f_h, and (c) elastic embedment stiffness, k_{el}. For spruce and birch tested in Series (1), (5) and (6), mean curves are given in (a), while boxplots in (b) and (c) express the median values and variation (25th and 75th percentile) for f_h and k_{el}, respectively.*

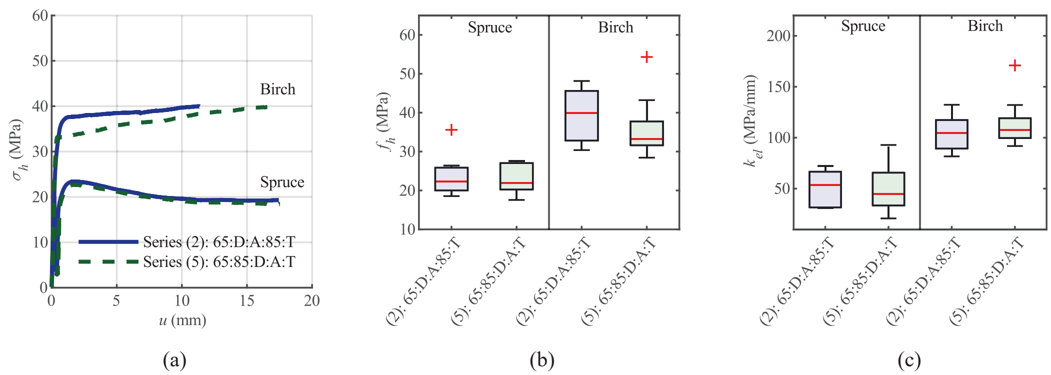

Figure 5: *Influence of the assembly history, for the high MC condition (tested at MC20/85), on (a) embedment stress-displacement curve, (b) embedment strength, f_h, and (c) elastic embedment stiffness, k_{el}. For spruce and birch tested in Series (2) and (5), mean curves are given in (a), while boxplots in (b) and (c) express the median values and variation (25th and 75th percentile) for f_h and k_{el}, respectively.*

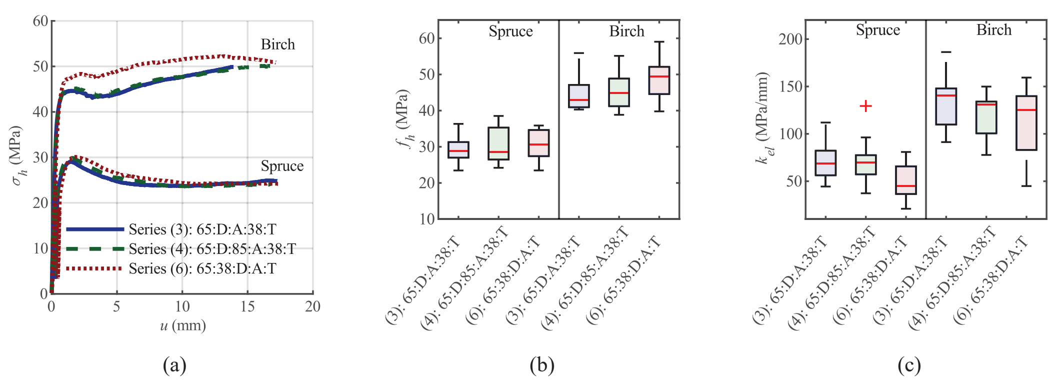

Figure 6: *Influence of the assembly history, for the low MC condition (tested at MC20/38), on (a) embedment stress-displacement curve, (b) embedment strength, f_h, and (c) elastic embedment stiffness, k_{el}. For spruce and birch tested in Series (3), (4) and (6), mean curves are given in (a), while boxplots in (b) and (c) express the median values and variation (25th and 75th percentile) for f_h and k_{el}, respectively.*

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the series compared in this section, is the assembly history, while the MC at testing (either high or low MC) and the mean specimen density are always the same.

The embedment stress-displacement curves in Figure 5(a) and Figure 6(a), show for both wood species similar shapes and stress levels independent from the assembly history. Curves for spruce exhibit an almost perfect overlay. Curves for birch however show small differences, where for high MC condition the reference curve showed lower resistance, while for the low MC condition the reference curve exhibited higher resistance compared to the corresponding reference series.

The embedment strengths, f_h, illustrated by boxplots in Figure 5(b) and Figure 6(b), reflect the observations from the embedment stress-displacement curves. For spruce, the difference in the average f_h between the series was smaller than 5%, in low and high MC conditions. The corresponding difference for birch was slightly larger amounting up to about 10% in the low and high MC cases. Thus, a significant influence of the assembly history on f_h was not observed.

The elastic embedment stiffness, k_{el}, shown in Figure 5(c) and Figure 6(c), exhibited a different behavior for the high and low MC situation. While hardly any influence of the assembly history was seen when the specimens were moistened (less than 10% difference), a more distinct influence was seen when the specimens were dried, especially for spruce. For the cases at which the dowel was assembled before the specimen was dried, namely Series (3) and (4), an about 50% higher average k_{el} was found for spruce (for birch up to 20% difference) compared to the reference case (Series (6)). This might be explained by pre-stressing of the wood matrix around the steel dowel, due to shrinkage caused by decreasing MC. Thus, small gaps might be closed during drying of the specimen, resulting in a tighter fit at testing, and additional friction at the sides of the dowel due to shrinkage in transverse fiber direction, might result in a higher k_{el}. However, results should be treated with care, since the stiffness parameter k_{el} exhibited a considerable variation in the results.

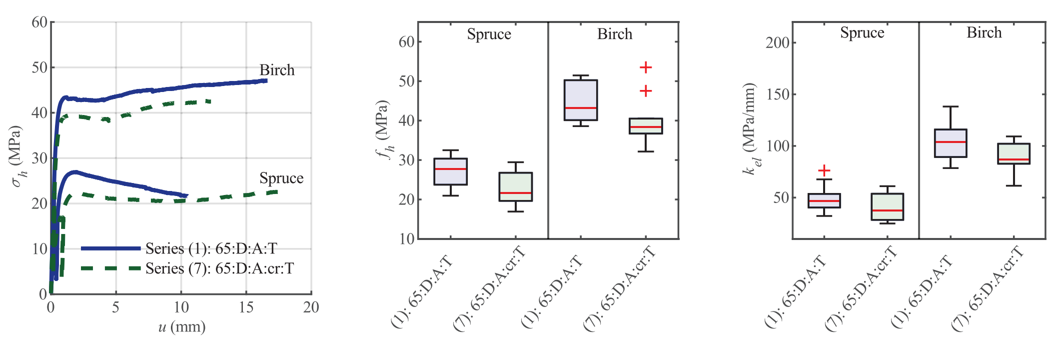
3.5 Influence of artificial cracks

Results from Series (1) and (7) are compared in Figure 7 to study the influence of an artificial crack on the embedment behavior. For both series, all the steps of drilling, assembly and testing were done at a moisture content corresponding to an ambient climate of 20°C and 65% RH. Compared to Series (1), specimens of Series (7) had an artificial crack in the wood below the dowel, representing a crack, which could develop at connectors during the service live of a building, e.g. due to moisture changes.

The embedment stress-displacement curves in Figure 7(a) show a clear difference in the embedment resistance when reaching the yield limit. A consistently higher embedment resistance was seen for the case without artificial crack (Series (1)). Both cases exhibit a similar curve shape, and a similar ductile behavior. Thus, also Series (7) did not show any global brittle failure, which can be explained by the applied reinforcement screws.

The embedment strengths, f_h, illustrated by a boxplot in Figure 7(b), reflect the observations from the embedment stress-displacement curves. Application of an artificial crack reduced the average embedment strength by about 10-15% for both investigated wood species. This might be explained by the reduced contact area below the dowel, and the reduced clamping effect of the dowel, since no tensile forces perpendicular to the grain can be transferred below the dowel, due to the artificial crack.

The elastic embedment stiffness, k_{el}, shown in Figure 7(c), was found to be slightly stronger influenced by the artificial crack as it was found for the embedment strength. The artificial crack reduced the average k_{el} by 15-20% compared to the uncracked case for both wood species. This might be explained by the aforementioned reduced clamping effect, which might affect the embedment stiffness more than the strength.



(a) (b) (c)

Figure 7: *Influence of artificial cracks on (a) embedment stress-displacement curve, (b) embedment strength,* f_h, *and (c) elastic embedment stiffness,* k_{el}. *For spruce and birch tested in Series (1) and (7), mean curves are given in (a), while boxplots in (b) and (c) express the median values and variation (25*th *and 75*th *percentile) for* f_h *and* k_{el}, *respectively.*

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4 CONCLUSIONS

The comprehensive experimental testing program gave valuable insights into the embedment strength and stiffness, as regards the influence of the moisture conditions relevant for practical applications during production, assembly, and testing. Similar observations for spruce and birch indicate validity of the findings for different wood species with different density. Thorough sampling and accurate production of the test specimens were key to isolate the influence parameters of (i) moisture content, (ii) assembly history, and (iii) artificial cracks, from other major influence parameters like wood density.

The wood moisture content had a distinct influence on the embedment strength. For increased moisture contents compared to the reference MC at 20°C and 65% RH, an increase in strength of 2-4% per % MC was found, while for decreased moisture contents a decrease in strength by 4-6% per % MC as compared to the reference MC. In contrast, no distinct influence of the moisture content on the embedment stiffness was seen.

The assembly history did not show a distinct influence on the embedment strength. However, an increase in the average elastic embedment stiffness of up to 50% was found when drying the specimen after assembly of the steel dowel at the reference condition. In contrast, no influence was seen when the specimen was moistened after dowel assembly.

The artificial cracks applied below the steel dowel over the entire specimen depth resulted in a reduction of the average embedment strength by 10-15%. An even stronger effect was seen for the elastic embedment stiffness, which was reduced by 15-20% by the artificial crack. Due to reinforcement of the specimens, no global brittle failure was seen, despite application of an artificial crack.

These findings are expected to give valuable information for numerical modelling of dowel-type connections, as well as for engineering design. Furthermore, the results of this study might help to interpret findings from structural health monitoring and field measurements, as it shows the development of local connection stiffness with moisture changes in respect to the assembly history. In addition, the study highlighted the challenge of accurate stiffness measurement, which was reflected in a comparable high variation in stiffness results. It is proposed that more attention should be paid to embedment stiffness determination for future experimental studies and to the development of future testing standards, since the need for suitable connection stiffness prediction increases with the development of complex modern timber structures, like taller timber buildings.

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