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HUMIDITY IMPACT ON TIMBER CONNECTION STRENGTH

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ABSTRACT: The effects of climate change in several regions of the world include increased rainfall, which can lead to moisture ingress into buildings. This issue is particularly problematic for timber structures due to potential defects in waterproofing that can lead to direct contact with water, which can cause timber decay and a decrease in strength, as moisture becomes trapped between permeable and impermeable surfaces, e.g. within a timber frame wall panel. While the effect of moisture on timber strength properties is well known, its impact on timber connections is less studied. Timber connections usually involve dowel-type fasteners, creating a tight-fit joint where any expansion of wood due to increased moisture content is hindered by the fastener holding the members together. This study examined the effect of moisture on the strength of timber connections, particularly focusing on the additional stresses in the connection, caused by hindered expansion of wood in two scenarios: 1) timber with high moisture content and 2) timber subjected to cyclic changes in moisture content. The experimental tests indicated that there is no effect of additional stress build-up in such connections on the withdrawal strength, although an instance of screw brittle failure observed during testing requires further studies. The cyclic changes in hygrothermal conditions were found to significantly affect embedment strength of OSB.

KEYWORDS: timber connections, durability, moisture, timber expansion

1 – INTRODUCTION

The effects of climate change are becoming increasingly evident, particularly through increased rainfall in regions already experiencing heavy precipitation, such as the UK. Since timber strength and stiffness are known to be adversely affected by high moisture content (MC), the rising humidity and the associated risk of moisture ingress due to rainfall and flooding present an urgent issue to be addressed.

This study focused on timber connections, which are often the critical design aspects in timber structures. Timber joints typically consist of at least two timber members, or a steel and a timber member, connected by a dowel-type fastener, creating a tight joint. In such connections, in addition to the adverse effects of high moisture on timber material properties, there may be additional strength loss due to the stress build-up from the restricted expansion of the wooden member(s), see Fig. 1. This study aimed to experimentally quantify the effects of that additional stress build-up in such connections.

Typical connections in timber structures use screws, nails, or bolts to transfer forces through withdrawal, bearing, or a combination of both. Timber strength generally decreases with increasing moisture content up to the fibre saturation point (FSP) [1], which in timber is about 30%, while the increase of moisture content above the FSP has been found to have little effect. Studies of screw withdrawal found that at 60-70% MC, withdrawal strength was 30-40% less for softwood and 36-42% less for hardwood compared to the dry state [2][3]. High moisture content was noted to impact strength negatively, but cyclic humidity changes (wet-dry) could be even more significant, especially for wood-based panels, such as oriented strand board (OSB) [4]. For screws in treated softwood, after 12 wet-dry cycles a 13% and 48% decrease was observed in withdrawal capacity parallel and perpendicular to the grain, respectively [5]. In a similar study by [6], after the 3rd cycle of wetting-drying, the withdrawal strength of screws in treated softwood decreased; however after the 6th and 12th cycle it increased, and then it decreased again after the 24th cycle. For OSB/3, after 10 wet-dry cycles, the screw withdrawal strength was found to be reduced by 60% [7]. In terms of lateral loading, a 14% decrease in softwood embedment strength was found between 12% and 19% MC, with the

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strength beyond FSP remaining constant but 40% less than at 12% MC [8].

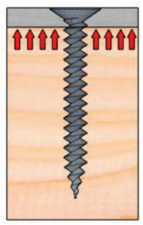

Figure 1: Example of a connection with restricted expansion.

While these studies show a general decrease in strength for single fastener connections, they do not address the increased internal stress build-up at the members' interface (see Fig. 1) due to potential expansion of wood and wood-based members in the joint.

2 METHODOLOGY

The testing regime included withdrawal and embedment tests of nails and screws from sawn wood and a wood-based panel. The sawn wood used in the study was treated timber of class C16, and untreated timber of class C24, according to BS EN 338:2016 [12]. The wood-based panel was a 9-mm sheet of OSB/3.

To understand the effect of the confined stress build-up at the tight interfaces of the joints, a metal-to-timber connection was investigated. Due to large swelling at high moisture of OSB, a test configuration with a metal plate and OSB was also included in the test regime. To understand the effect of the cyclic hygrothermal changes, both withdrawal and embedment tests were performed (see Fig. 2 and Fig. 3).

The embedment tests included three variations:

- Nail inserted in OSB (*E-o-n*)
- Nail inserted in treated wood (*E-wt-n)*
- Screw inserted in treated wood *(E-wt-s)*

The withdrawal tests included five variations:

- Screw inserted in treated wood (*W-wt-s*)
- Screw countersunk into aluminium plate and inserted in treated wood (*W-wt-s-p*)
- Screw countersunk into aluminium plate and inserted in OSB and in treated wood (*W-wt-s-p-o*)
- Screw inserted in untreated wood (*W-wu-s)*
- Screw countersunk into aluminium plate and inserted in untreated wood (*W-wu-s-p*)

The specimens underwent three different hygrothermal conditioning regimes:

- *Regime 'Room'* – Conditioning at 65% RH and 20°C for one week, until constant mass has been achieved, defined as two successive mass weightings not differing by more than 0.1%, according to BS EN 383:2007 [9].
- *Regime 'Wet'* – soaking in water bath at room temperature for 3 weeks except for tests: *W-wt-s-p-o*, *W-wu-s* and *W-wu-s-p*, which were soaked for 2 weeks.
- *Regime 'Cyclic'* – Three cycles, each lasting one week and consisting of: soaking in water bath at room temperature for 70h, freezing at -5°C for 24h, drying at 15°C for 7h, drying at 40°C for 65h and conditioning at 20°C and 65% RH for 4h. After the last cycle the specimens were conditioned at 20°C and 65% RH for additional 20h. This regime follows from BS EN 321:2002 [10], with some adjustments to the temperatures, in order to represent the upper and lower boundaries of typical weather conditions in the UK.

Before undergoing the specific hygrothermal regimes, the specimens used in *Wet* and *Cyclic* regimes were conditioned according to *Room* Regime. The test matrix is listed in Tab. 1. The fasteners used in the tests are shown in Fig. 4.

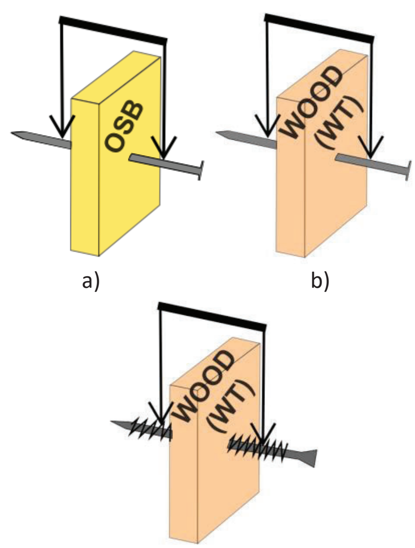

Figure 2: Schematics of the embedment tests: a) E-o-n, b) E-wt-n, c) E-wt-s

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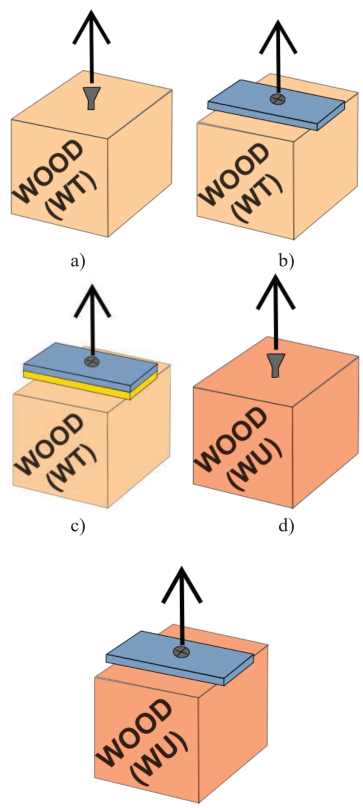

Figure 3: Schematics of the withdrawal tests: a) W-wt-s, b) W-wt-s-p, c) W-wt-s-p-o, d) W-wu-s, e) W-wu-s-p

Fig. 4: Fasteners used in the tests: top: nail (nails had an adhesive strip for nail gun), bottom: screw

The dimensions of the specimens used for embedment tests followed from the requirements in BS EN 383:2007 [9]. The OSB/3 specimens used for the embedment tests (*E-o-n*) were all 9 mm thick – proceeding from a 9-mm-thick sheet, while the timber specimens in the embedment tests had mean thickness of 8.1 ± 0.8 mm (*E-wt-n & E-wt-s*) and were cut from a larger timber stud. The loading rate was 0.8 mm/min, and the test was stopped after the maximum force was reached. The dimensions of the specimens for withdrawal followed from the minimum requirements given in BS EN 1382:2016 [11]. The withdrawal loading rate was 1.2 mm/min, and the test was stopped after the load dropped to 80% of the maximum recorded load. The test setups are shown in Fig. 5.

3 – RESULTS AND ANALYSIS

3.1 Embedment tests

All embedment tests failed in bearing under the fastener, which is the expected failure mode. The embedment capacity, F_h, was assessed at the intersection of the line fitted to the linear section of the plot and offset by $0.1d_{nom}$ (nominal diameter of the fastener) with the load-displacement data, according to D 5764 – 97a [13]. The embedment strength was calculated as the embedment capacity, F_h, divided by fastener effective diameter, d_{eff}, and by specimen thickness, t. The effective diameter was defined as 1.1 x root diameter for screws and as nominal diameter for nails. In order to compare the data across the tests, the strength values were adjusted by initial density, ρ_{int}, measured before the testing but after the initial conditioning (at 65% RH and 20°C). The embedment results are plotted in Fig. 6 and are listed in Tab. 2.

Table 1: Test matrix.

Test ID	Wood (or wood-based) member size [mm]	Fastener size [mm]	No. of tests in Regime		
			Room	*Wet*	*Cyclic*
E-o-n	*o* 35 x 125 x 9	*n* 3.1 x 90	10	10	10
E-wt-n	*wt* 35 x 125 x 9*	*n* 3.1 x 90	9	10	10
E-wt-s	*wt* 50 x 195 x 9*	*s* 5 x 70	8	9	7
W-wt-s	*wt* 70 x 100 x 100	*s* 5 x 70	9	10	7
W-wt-s-p	*wt* 70 x 100 x 100	*s* 5 x 70	–	10	7
W-wt-s-p-o	*wt* 70 x 100 x 100	*s* 5 x 70	–	6	–
W-wu-s	*wu* 45 x 100 x 95	*s* 4 x 70	–	10	–
W-wu-s-p	*wu* 45 x 100 x 95	*s* 4 x 70	–	9	–

Notes for the table: *E* – embedment, *W* – withdrawal, *wt* – treated sawn wood C16, *wu* – untreated sawn wood C24, *o* – OSB/3, *p* – 10-mm-thick aluminium plate, *n* – nail with circular screw shank [nominal diameter x length], *s* – countersunk head, partially threaded screw, 40 mm threaded length, [nominal diameter x length], * - actual thickness was 8.1 ± 0.8 mm due to cutting difficulties

a) b) c) d) e) f)

Figure 5: Set-ups of the tests: a) E-o-n, b) E-wt-n, c) E-wt-s, d) W-wt-s & W-wu-s, e) close-up on the screw head in tests W-wt-s & W-wu-s, f) W-wt-s-p & W-wt-s-p-o & W-wu-s-p

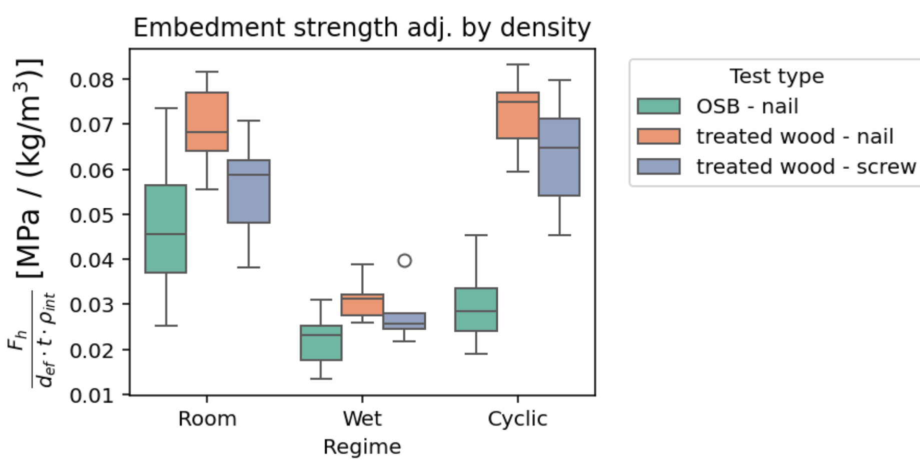

Figure 6: Embedment test results; line in box shows median, outliers shown as circles.

For sawn wood (*E-wt-n & E-wt-s)* using wet conditions, the embedment strength-adjusted-by-density values are 44-46% (see Tab. 3) of the values using room conditions (comparing medians), which is expected, as timber material properties are known to degrade with increasing moisture content up to the saturation point. The Wet regime in this study represents the saturation state (>30% MC). For sawn wood in Cyclic regime, a 10% increase (comparing medians) was observed in the values compared to Room regime. It should be noted that the specimens at the Cyclic regime were tested at a slightly lower MC (approx. 10% MC, tab. 2), compared to Room Regime (approx. 13%, MC tab. 2). This finding implies that cyclic changes (of the length and repetitions used in this study) in the hygrothermal conditions do not affect sawn wood embedment strength – strength increases with decreasing MC, which is a known property of timber material strength.

For OSB (*E-o-n)* using wet conditions, the embedment strength-adjusted-by-density values are 51% of the values using room conditions (comparing medians) – similar degradation to sawn wood discussed above. For

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Table 2: Test results showing mean values and standard deviation.

Test description	Test ID	Regime *Room*			Regime *Wet*			Regime *Cyclic*		
		ρ_{int} [kg/m^3]	MC [%]	F_{obs} [kN]	ρ_{int} [kg/m^3]	MC [%]	F_{obs} [kN]	ρ_{int} [kg/m^3]	MC [%]	F_{obs} [kN]
OSB – nail	*E-o-n*	625.9 ± 27.2	9.0 ± 0.2	0.82 ± 0.26	625.1 ± 27.3	119.9 ± 6.6	0.38 ± 0.10	595.8 ± 19.6	9.6 ± 0.3	0.50 ± 0.16
Treated wood – nail	*E-wt-n*	489.8 ± 52.5	12.7 ± 0.4	0.86 ± 0.13	494.5 ± 53.3	106.6 ± 8.5	0.36 ± 0.03	491.4 ± 34.5	10.6 ± 0.3	0.94 ± 0.18
Treated wood – screw	*E-wt-s*	415.3 ± 34.5	12.8 ± 1.3	0.62 ± 0.13	418.1 ± 39.3	121.8 ± 7.8	0.30 ± 0.08	414.0 ± 35.1	9.7 ± 0.3	0.75 ± 0.16
Treated wood – screw only	*W-wt-s*	429.5 ± 24.0	13.7 ± 0.3	5.18 ± 1.41	453.3 ± 42.1	82.8 ± 9.8	2.75 ± 0.64	418.1 ± 22.8	11.5 ± 0.4	5.37 ± 1.14
Treated wood – screw with plate	*W-wt-s-p*	–	–	–	432.3 ± 35.3	87.8 ± 8.6	2.56 ± 0.41	427.7 ± 20.1	11.1 ± 0.6	5.42 ± 1.25
Treated wood – screw with plate & OSB	*W-wt-s-p-o*	–	–	–	427.2 ± 34.9	72.5 ± 4.0	2.77 ± 0.55 *	–	–	–
Untreated wood – screw only	*W-wu-s*	–	–	–	555.6 ± 12.5	54.1 ± 1.3	2.31 ± 0.51	–	–	–
Untreated wood – screw with plate	*W-wu-s-p*	–	–	–	554.3 ± 13.6	54.9 ± 1.3	2.69 ± 0.23	–	–	–

Notes for table: F_{obs} – F_h in embedment tests and F_{ax} in withdrawal tests, MC – moisture content immediately after test, ρ_{int} – density of the sample after initial conditioning at 20°C and 65% RH and before soaking or cyclic regime, * - excludes the test with screw failure

OSB in Cyclic regime, a 38% decrease (comparing medians) was observed in the values compared to Room regime. These findings imply that OSB experiences an irreversible loss of embedment strength due to hygrothermal cycles and does not regain strength even when dried to a low moisture content (approximately 10% MC, see Tab. 2). In contrast, sawn wood, after a reduction in strength caused by exposure to high humidity, recovers its strength as the humidity decreases.

Table 3: Differences in embedment strength across the hygrothermal regimes

Test ID	Strength adjusted by density, ratio:		
	Wet / Room	Cyclic / Room	Cyclic / Wet
OSB – nail (*E-o-n*)	0.51	0.62	1.23
Treated wood – nail (*E-wt-n*)	0.46	1.10	2.39
Treated wood – screw (*E-wt-s*)	0.44	1.10	2.52

3.2 Withdrawal tests

All tests failed in withdrawal of the screw from timber, except one test which resulted in screw failure. The withdrawal capacity, F_{ax}, was assessed as the maximum load in the test. The withdrawal strength (referred to as the withdrawal parameter in BS EN 1382:2016) was calculated as the withdrawal capacity, F_{ax}, divided by the fastener's effective diameter, d_{eff}, and the penetration length, l_{eff}. The penetration length for all tests was equal to the threaded length (40 mm), as all screws were partially threaded. In order to compare the data across the tests, the withdrawal strength values were adjusted by initial density, ρ_{int}, measured before the testing but after the initial conditioning (at 65% RH and 20°C). The withdrawal results are plotted in Fig. 7 and are listed in Tab. 2.

No clear difference in strength-adjusted-by-density values was observed for different test configurations in Wet Regime, which was further confirmed by carrying out the *Mann-Whitney U Test*, which output no statistical difference between any sample pair in this regime. This confirms that the confinement effect provided by the plate with or without the OSB layer underneath, does not in fact impact the withdrawal capacity of the screw from untreated or treated timber.

For treated wood (*W-wt-s)* in Wet regime the strength-adjusted-by-density values are 53% (see Tab. 4) of the values in Room regime (comparing medians) – similar degradation in strength as in embedment tests. For treated wood (*W-wt-s)* in Cyclic regime, a 23% increase (comparing medians) was observed in the values compared to Room regime. Similarly to the embedment tests, the specimens at the Cyclic regime were tested at a slightly lower MC (approx. 12%, Tab. 2), compared to Room Regime (approx. 14%, Tab. 2). Similarly to the findings for embedment strength, the cyclic changes (of

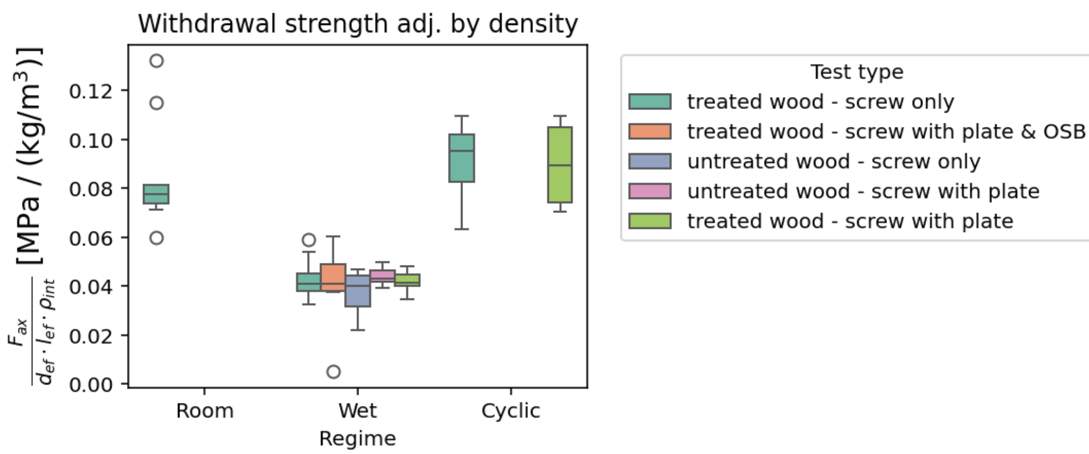

Figure 7: Withdrawal test results; line in box shows median, outliers shown as circles.

the length and repetitions used in this study) in the hygrothermal conditions (or accelerated aging) do not affect sawn wood withdrawal strength.

Table 4: Differences in withdrawal strength across the hygrothermal regimes

Test ID	Strength adjusted by density, ratio:		
	Wet / Room	Cyclic / Room	Cyclic / Wet
Treated wood – screw only (*W-wt-s*)	0.53	1.23	2.33
Treated wood – screw with plate (*W-wt-s-p)*	NA	NA	2.15

NA – configuration not tested

One of the tests in *W-wt-s-p-o* (treated wood – screw with plate & OSB) configuration resulted in a screw failure (Fig. 8). The failure was brittle and located at the beginning of the threaded part. This test is noted as the outlier in Fig. 7. The load recorded at failure was 0.29 kN which is approximately 10% of the expected capacity. Although no definitive explanation for this failure was found, discussions with Sara Keypoursangsari at the *University of Alberta* and Leonardo Diaco at *Rothoblass* (personal communication, February 10, 2025) suggest that the cause could be a change in the chemical composition of the screw (i.e., hydrogen embrittlement) in combination with high torque. The torque applied during screw insertion was not measured in this study, and therefore, this hypothesis cannot be confirmed or rejected based on the available data.

The brittle failure of the screw in test *W-wt-s-p-o* can be characterized by intergranular fracture, as observed in the SEM scan in Fig. 9a. For comparison, scans are included of two other screws*:* 1) a screw from test *W-wt-s-p-o* that failed in withdrawal and was subsequently tested in tension for the purposes of the SEM scanning; 2) a screw that failed due to high torque in pre-testing trials. No intergranular cracking is visible in the tensile screw or the torque screw (Fig. 9b-c), which aligns with the possibility that the brittle failure of the screw in test *W-wt-s-p-o* was caused by hydrogen embrittlement, which is typically characterized by intergranular failure, unlike tensile or torsion failure, which is characterized by microvoid coalescence and a rough, dimpled fracture surface.

Figure 8: top: test specimen with screw failure (W-wt-s-p-o), bottom: failed (fractured) screw and example of a screw that withdrew

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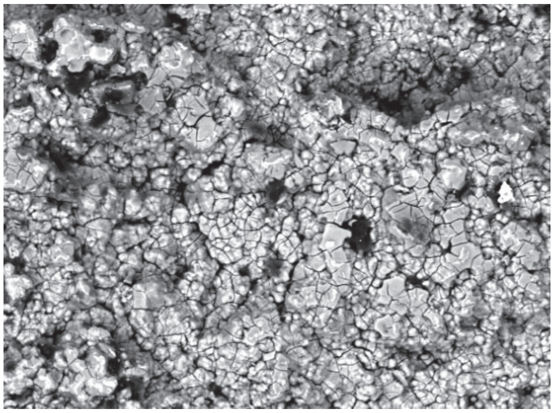

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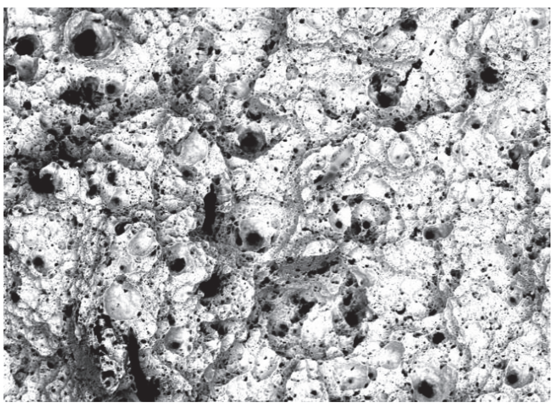

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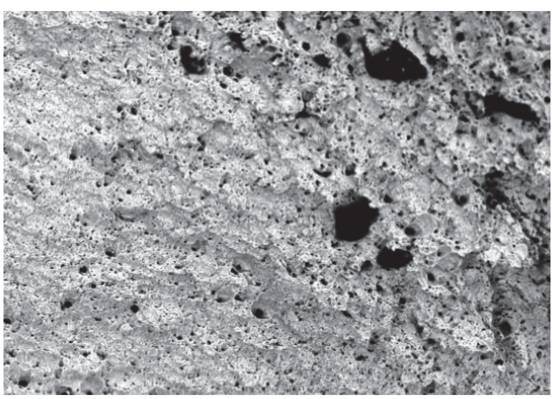

c)

Figure 9: SEM scans: a) screw suspected of failure due to hydrogen embrittlement, b) screw failed in tension, c) screw failed in torsion (200 magnification, 20 kV EHT)

4 – CONCLUSIONS

The anticipated additional strength loss due to the hindered expansion of timber in tight joints was not observed in this study. Based on the experimental data, the hypothesis that the stress build-up at tight interfaces between the timber and steel members lowers the withdrawal capacity of the connection was rejected.

However, the observed brittle failure of the screw at a very low withdrawal load in a tight connection consisting of an aluminium plate, OSB and sawn wood is an important finding that requires further investigation. The data gathered in this study was not sufficient to explain the reason for the screw fracture at such low loads.

Another key finding from the study is the irreversible degradation of the embedment strength in OSB after cyclic changes of hygrothermal conditions, which was found to be approximately 60% of the initial strength. The sawn wood did not show any degradation after the cycles performed in this study, i.e. three cycles each lasting one week.

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