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EXPERIMENTAL TESTING OF SMALL-SCALE TIMBER-CONCRETE COMPOSITE BEAMS UTILIZING ADHESIVE SHEAR CONNECTIONS

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ABSTRACT: Timber-concrete composite (TCC) structural elements have shown desirable mechanical characteristics for use in the structural design of mass timber buildings. Most shear connections used in TCC elements are not perfectly rigid. However, a nearly full composite behaviour can be achieved in TCC sections that utilize adhesive for their shear connections, which significantly increases the stiffness and strength of the resulting sections. Due to the costs and logistics of large-scale studies, an experimental program was conducted to test small-scale TCC beams from a black spruce glulam section. Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and compression tests were conducted on two groups of samples. The first group was for small-size beams with no concrete layer on top, that were taken from a glulam beam section, and consisted of three sub-groups: Group A for beams with no glue line present; Group B for beams with one horizontal glue line at mid-depth between two lamellae; and Group C for beams with one vertical glue line at the beam midspan. The second group was for small-size TCC beams that utilized adhesive for their shear connections and consisted of three sub-groups: Group D for TCC beams with 28-day concrete age that utilized wet-on-dry adhesion process; Group E for TCC beams with 7-day concrete age that utilized wet-on-wet adhesion process; and Group F for TCC beams with 28-day concrete age that utilized wet-on-wet adhesion process. Each sub-group consisted of 10 samples for determining the MOE and MOR and another 10 samples for the compression tests. Additionally, Scanning Electron Microscope images were taken for the adhesive lines between the wood lamellae highlighting how a perfectly rigid connection can be developed using adhesive. The results for the glulam beam specimens were found to have a low coefficient of variability and are close to the results published in the available literature. This suggests similar characteristics of glulam made from small diameter trees on both small and large scales. In contrast, the results of the TCC beam specimens were more variable due to the application of two different adhesion methods (i.e., wet-on-wet, and dry-on-wet methods). Also, all test specimens experienced brittle failures.

KEYWORDS: Timber-concrete composite (TCC) sections, Glulam, Adhesive shear connections, Composite action

1 INTRODUCTION

Timber-concrete composite (TCC) systems have been proven to provide many benefits over conventional timber or reinforced-concrete floor systems [1]. TCC systems have seen increased use in new construction and the rehabilitation of existing timber structures. Such composite systems rely on various shear connectors to develop the composite action between the timber element carrying the tensile forces and the concrete topping layer having the compressive forces. Brittle failure can occur in the timber element and the concrete layer. The type and mechanical characteristics of the utilized shear connectors can influence the failure mode (i.e., brittle, or ductile) of a TCC system [2]. While mechanical shear connectors, such as screws and steel plates, are approved for specific composite systems in the EU, none of these connectors guarantee perfectly rigid composite action. Therefore, initial stiffness for a TCC section is reduced when calculated using the gamma method. TCC systems with adhesive shear connections can achieve perfectly rigid behaviour in both small [3] and large-scale tests [4]. Adhesives connections can be applied either in a dry-on-wet method between a timber element and a cured concrete section or in wet-on-wet method, where a mass timber element has adhesive applied to it and fresh concrete is poured on top before the adhesive sets.

Full-size tests of TCC elements can be costly and time consuming, and storage constraints can limit the number of samples produced in an experimental setting. Small-scale tests can be more cost effective, and the smaller size of elements can allow for a greater number of samples to be produced. A greater number of specimens can increase confidence in the test results and be used as a cost-effective pilot project before committing resources to a large-scale testing program. However, mass timber elements can be difficult to scale down proportionally while maintaining their mechanical properties. For example, glued-laminated timber (glulam) and cross-laminated timber (CLT) elements are stronger than their individual lamina, so using clear samples of the wood

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species in the lamina would not provide the same results as a proportionally scaled down mass timber element. Before committing to a large-scale experimental program on TCC floor slabs with an adhesive connector and in accordance with ASTM-143-14 [5] standard requirements, this study investigated:

- the effect of the adhesive bond line between small-diameter, black spruce glulam wood elements themselves;
- whether these glulam elements could be used to represent the behaviour of a mass timber floor element in a TCC flexure beam, with a perfectly rigid adhesive connection;
- the difference on results between the wet-on-wet and dry-on-wet application process; and
- whether the strength of a small-scale TCCs concrete element was more accurately reflected through conventional sized testing cylinders or compression columns sized to ASTM-143-14.

2 EXPERIMENTAL PROGRAM

2.1 SPECIMENS DETAILS

In accordance with ASTM-143-14 standard, specimens tested for determining the MOE and MOR measured 300 mm in length and 20 x 20 mm cross-sectional dimensions. Whereas the specimens tested in compression had a height of 60 mm and 20 x 20 mm cross-sectional dimensions. Black spruce of 24F-ES stress grade was used from a glulam beam section for the timber elements. The glulam beam was composed of finger-jointed lamina with cross-sectional dimensions of 25 mm x 50 mm made from small diameter black spruce harvested between 80 and 120 years of age. The relevant mechanical properties are summarized in Table 1.

Table 1: *Mechanical properties of black spruce glulam [6]*

Product name	Nordic Lam
Stress grade	24F-ES/NPG
Comp. parallel to grain	33.0 MPa
Tension parallel to grain	20.4 MPa
Modulus of elasticity	13100 MPa

The compressive strength values of the two concrete batches used in the MOE/MOR specimens and compression specimens are summarized in Table 2. Due to the small size of the samples, a regular concrete mixture could not be used, as the maximum aggregate size is typically not greater than 1/3 the depth of the concrete layer so a number 6 sieve, with an opening of 3.35 mm was used to sieve the materials, resulting in a reduced concrete strength, based on the assumption of the concrete element having a slab thickness of 10 mm.

Table 2: *Average compressive strengths of concrete cylinders (MPa)*

Batch No.	1 (dry-on-wet)	2 (wet-on-wet)
7-day concrete age	15.8	15.4
28-day concrete age	19.74	20.1

To cast a TCC element in a wet-on-wet process, mimicking the process of casting a TCC section in place instead of prefabricating it, required the specification of a moisture insensitive adhesive capable of bonding wet concrete to timber. Sikadur®35 Hi-Mod [7] was selected. It is classified as a moisture insensitive, two-component structural epoxy with a 14-day shear strength of 41.0 MPa and a pot life of 30-38 mins. To ensure a proper bond, after the adhesive is applied, the concrete must be poured on top and packed into the form (without disturbing the adhesive) within 30 minutes.

Specimens for flexure bending tests had three different material cross sections: clear black spruce from a glulam beam, two black spruce laminae with an adhesive connection passing through the cross-sections centroid either vertically or horizontally aligned to the load as seen in Figure 1, and TCC elements with equal depths of concrete and black spruce with the concrete element oriented towards the load as seen in Figure 2.

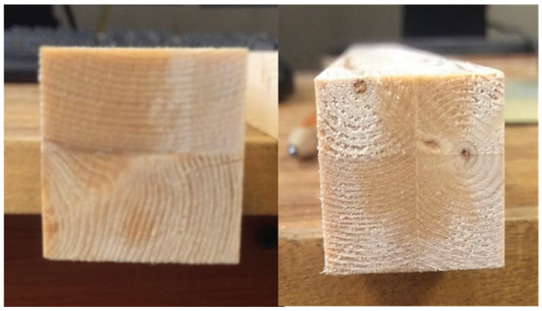

Figure 1: *Sample glue line orientation for MOE and MOR samples, mid-depth (left) and perpendicular to mid-depth (right)*

Figure 2: *TCC flexure specimens*

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2.2 SPECIMENS PREPERATION

Pieces of wood were cut from a glulam beam section and sized to be either 10 mm or 20 mm (deep) by 20 mm (wide) and 355 mm long for the bending tests and 60 mm tall for the compression tests. Samples were placed in a conditioning chamber at 20 ˚C and 65% relative humidity for a week, to bring their moisture content to 12% as required by ASTM D4933-16 [8].

For TCC elements, Sikadur®35 Hi-Mod was applied to the 10 mm deep glulam elements and either topped with concrete in a wet-on-wet process and allowed to cure for 7 or 28 days in forms before testing, or applied to previously cast, 10 mm deep, 20 mm wide, 355 long concrete elements in a dry-on-wet process and tested at 28 days. All concrete elements were lightly vibrated, covered with plastic to retain moisture, and lightly misted for the first seven days.

2.3 TEST SETUP

The test program consisted of 60 three-point flexure bending specimens and 70 compression samples, consisting of 10 samples in each of Group A to F and A to G, respectively. The respective test variables of the specimens are summarized in Table 3 for the three-point flexure bending tests and in Table 4 for the compression tests.

The MOE is a measurement of the stress-strain relationship within a material and describes the stiffness of a material with respect to the allowable amount of elastic deformation before full recovery is no longer possible. The MOR is a measurement of the maximum bending capacity of a sample before failure occurs.

Table 3: *MOE and MOR test matrix*

Group	Material (cure time)	Glue line location	Concrete batch No.
A	Glulam	Perp. to mid-depth	N/A
B	Glulam	Mid-depth	N/A
C	Glulam	N/A	N/A
D	TCC (28-day)	Mid-depth	1
E	TCC (7-day)	Mid-depth	2
F	TCC (28-day)	Mid-depth	2

The compression resistance parallel to wood grain was tested as this type of load occurs in both axially loaded columns, as well as the top fibres of beams undergoing flexure bending. Compression tests were done on small-size columns of concrete as well as glulam and TCC sections as the compressive strength of a concrete sample scaled to ASTM-143-14 would more accurately reflect the compressive strength of the concrete element in the TCC sections as opposed to the results of a full-size test cylinder.

TCC elements undergoing three-point flexure bending in groups E and F made with a wet-on-wet process were tested at 7 days in addition to 28 days as in-situ where a wet-on-wet process could be used with a mass timber elements acting as the formwork for the concrete, as the TCC element could reasonably be expected to take some loading at 7 days. Samples in Group D made with the dry-on-wet process reflect a prefabricated TCC section which would not be loaded until the concrete had cured for 28 days or much longer before being bonded to a mass timber element at a factory or on site.

Table 4: *Compression tests matrix*

Group	Material	Concrete batch No.	No of days
A	Glulam	N/A	N/A
B	Glulam	N/A	N/A
C	Glulam	N/A	N/A
D	TCC	1	28
E	Concrete	2	7
F	Concrete	2	28
G	Concrete	1	28

The MOE and MOR tests were conducted using the three-point Tinius Olson H10KT testing machine (Figure 3); while for the compression tests, the Tinius Olsen Universal Testing Machine H50KT was utilized in accordance with ASTM-143-14 testing standard.

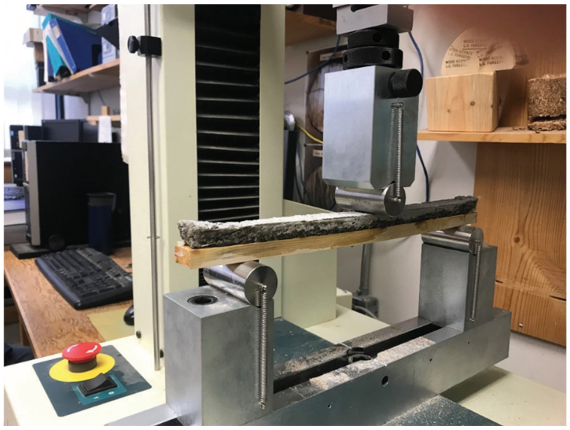

Figure 3: *Three-point flexure bending test with computer registered failure*

Samples were loaded until the machine detected a failure, as shown in Figure 4, during a compression test of a TCC column.

Once loading of a test specimen stopped, failure modes were observed and recorded. Based on the registered load and corresponding deflection, the MOE, MOR, and the compression resistance parallel to wood grain were all determined. Each group had 10 samples to ensure

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reasonable consistency and thus, the co-efficient of variation (CV) was calculated to determine the relative consistency of the results.

Figure 4: Computer registered failure of a TCC column under compression

2.4 MICROSCOPIC STUDY

In addition to the mechanical properties testing, a microscopic study was undertaken to observe the adhesive interface between black spruce lamina from the glulam section and to visually highlight its effectiveness. A Scanning Electron Microscope (SEM) provides high resolution images by using electrons to bombard a sample and interpret the measured results into a digital image. The Hitachi Su-70 Schottky Field Emission SEM used in this study is in the Wood Science and Testing Facility at Lakehead University. Small cubes measuring 1 mm on all sides were cut from the pieces that were used for sectioning with the microtone. The electrical nature of this type of microscope requires biological samples to be coated in gold before being placed in the machine.

Detailed features seen in the cross-sectional plane from the SEM imagery include resin canals, early wood, and latewood tracheid (the latewood cells being particularly small and dense), and the wood-glue-wood interface between laminates is seen in Figure 5.

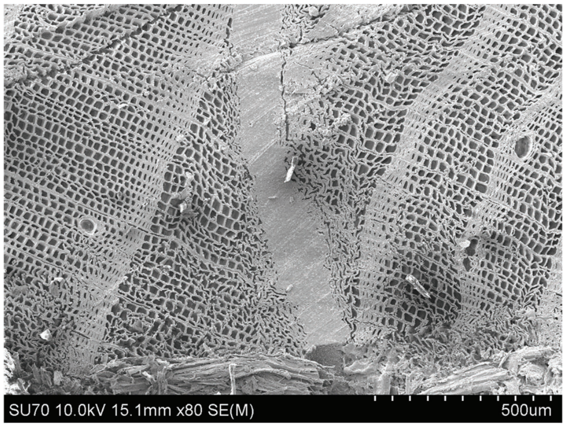

***Figure 5:** Glulam SEM cross-section overview*

The SEM microscopy showed that many of the longitudinal tracheid are crushed and broken during the lamination process as can been seen in the cell walls near the glue line and within the glue, as shown in Figures 6 and 7.

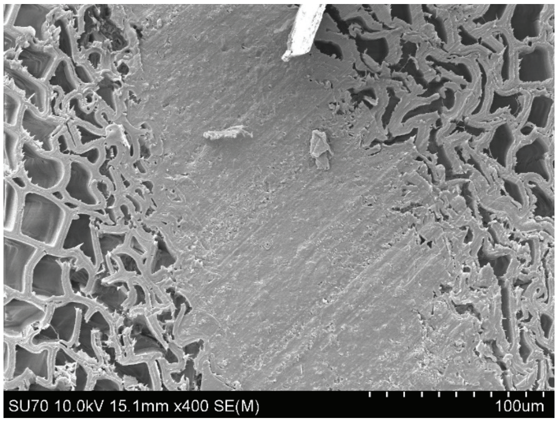

***Figure 6:** Glulam SEM cross-section with glue line details*

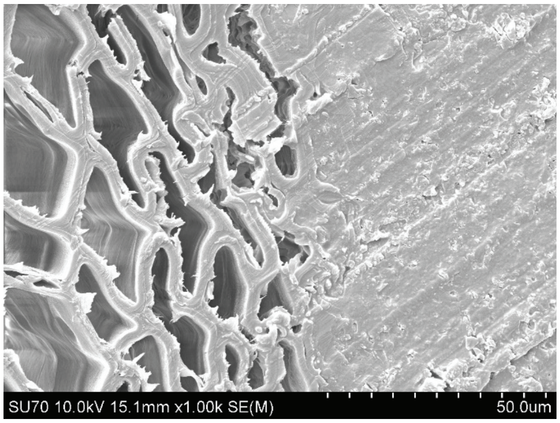

***Figure 7:** Glulam SEM cross-section, glue-wood line detail*

The completeness of the wood-glue bond can be seen in Figure 8, where the glue is shown to seamlessly be bonded along the longitudinal tracheid cell walls both between the laminates and away from the glue line.

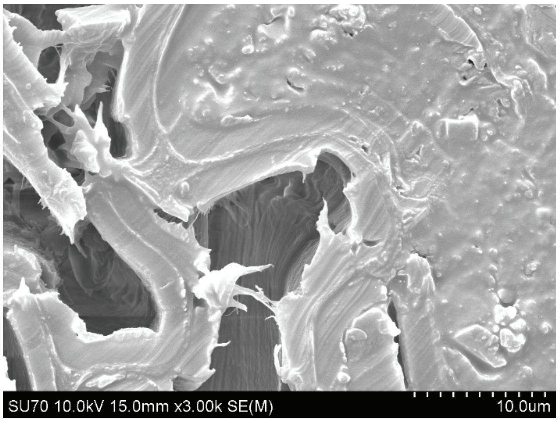

Figure 8: *Glulam SEM cross-section, showing glue-wood bond detail*

3 RESULTS

3.1 MECHANICAL

The MOE and MOR test results are summarized in Table 5; whereas Table 6 shows the compression test results. Test specimens in Group D from Table 5 used concrete from batch No. 1 and specimens in Groups E and F used concrete from batch No. 2.

Table 5: *MOE and MOR test results*

Group ID.	MOE		MOR	
	Value (MPa)	CV (%)	Value (MPa)	CV (%)
A (glulam)	19,990	9.6	95.3	10.6
B (glulam)	17,566	20.7	88.0	19.8
C (glulam)	10,957	12.7	85.8	9.8
D (TCC-dry, 28-day)	8,646	15.7	50.4	28.6
E (TCC-wet, 7-day)	6,327	21.8	31.7	13.4
F (TCC-wet, 28-day)	6,629	28.7	38.7	24.0

Table 6: *Compression column test results*

Group ID.	Value (MPa)	CV (%)
A (glulam)	48.6	5.3
B (glulam)	49.7	11.1
C (glulam)	46.0	9.8
D (TCC, 28-day)	27.2	22.5
E (concrete, 7-day)	7.64	26
F (concrete, batch 2, 28-day)	13.71	19.6
G (concrete, batch 1, 28-day)	20.4	18.7

The compression columns, from Table 6, tested in Groups D and G were made using concrete from batch No. 1, and concrete compression columns in Groups E and F were made using concrete from batch No. 2.

3.2 FAILURE MODES

3.2.1 Three-point flexure bending

In the three-point flexure bending tests, samples from Groups A, B and C all experienced brittle tensile failure in the wood, as shown in Figure 9. Group A had different break patterns than those of Groups B and C. Group A specimens would often see a tensile break across the bottom of only one lamina (half the width of the cross section due to the vertically oriented glue line). Failure in Groups B and C was characterized by a break across the width of the entire singular lamina (Figure 9). Typically, all failures occurred around a defect in the wood, such as a knot or a finger joint.

Figure 9: *Typical tensile failure mode in glulam samples*

Failure in the TCC beams almost always occurred in the concrete and was characterized by very sudden and brittle failure. Occasionally, some of the concrete at the adhesive bond would shear off after vertical or diagonal cracking appeared at the midspan, resulting in a section of the concrete flying away as the wood beam rebounded due to the load being removed by the machine after it detected the failure in the concrete, as shown in Figure 10.

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Figure 10: *Sudden and brittle shear failure near the adhesive interface*

Other observed failures modes include local crushing in the top concrete layer near the point load (Figure 11), diagonal shear cracks in the concrete (Figure 12) or vertical separation above the adhesive interface indicating a reduced area of effective adhesive (Figure 13).

Figure 11: *Local crushing from compression near the applied load*

Figure 12: *Diagonal shear crack at failure*

Figure 13: *Shear along adhesive interface (indicative of epoxy quality control) with some shear failure in concrete*

A small number of TCC samples appeared to have failed due to tensile failure in the wood as seen in Figure 14.

Figure 14: *Tensile failure in wood component*

However closer inspection of these samples often showed small cracks in the concrete as seen in Figure 15, suggesting the concrete had failed and transferred the load to the wood, resulting in a tensile splitting failure.

Figure 15: *Shear crack visible in concrete close to tensile failure zone in timber*

3.2.2 Compression

For Groups A, B and C, the wood samples experienced typical compressive failure modes in the wood fibres as shown in Figure 16.

Figure 16: *Compression specimens from Groups A, B and C*

Failure in Group D, the TCC columns, was typically observed in the wood, after some cracking in the concrete, as shown in Figure 17.

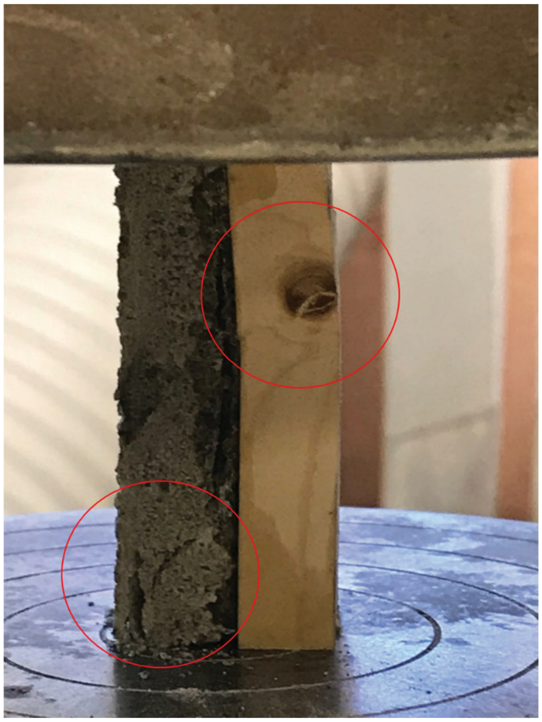

Figure 17: *Failure in timber and concrete in the composite column compression test*

This suggests that the failure of the timber after the concrete stopped contributing to the load-carrying capacity and thus, the load path progressed through the timber element only. The damage in the timber is around the circled knot, a stress concentration area, and the damage in the concrete is at the base, suggesting a bearing failure that crushed the concrete locally.

The small-scale concrete columns, typically failed without cone development and thus, failure predominantly followed vertical lines. This may have been due to the square shapes of the columns and their small size. In some cases, the column crumbled to very small parts as seen in Figure 18. The compressive strength of the small-size compression samples (Figure 18) was a more accurate representation of the concrete's compressive strength in the TCC flexure beams than the strength of the full-size compression test cylinders.

Figure 18: *Failure in timber and concrete in the composite column compression test*

4 DISCUSSION AND RECOMMENDATIONS

From the flexure bending tests results, specimens in Groups A and B had significantly higher MOE values than those in Group C, by a factor of 1.8 and 1.6, respectively. This suggests that adhesive bond between the lamina and orientation of the growth rings allowed for loading to be better distributed around defects in the lamina compared to the specimens in Group C which came from the same glulam section but were clear wood samples. The MOE, MOR, and compression resistance values for the clear black spruce samples in Group C were in line with the values found in literature for the same species of tree and harvest region [9]. The modulus of rupture in all three glulam groups was similar with an increase of 5% and 10% in MOR for Groups B and A, respectively. From the MOE and MOR results from Group A and B, it is shown that the presence of glue lines increased the MOE but not the MOR compared to the clear wood specimens in Group C, suggesting that small diameter black spruce elements glued together and tested at the small scale can model the increased stiffness of built-up timber sections used in full-scale testing.

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The timber elements were moisture conditioned prior to application of the adhesive and bonding with fresh or dry concrete in line with previous experimental work on TCC elements [10]. Extensive shear tests have shown that in typical applications, failure will occur in either the timber or concrete elements before the adhesive if enough surface area is covered [11]. From the tests of the present study, it was seen that in all TCC bending tests the concrete elements failed. This was expected as the timber and concrete elements had equal cross-sectional areas under bending; however, the compressive strength of the concrete was appreciably lower than either the tensile or bending strength of the timber elements in the small-scale TCC beams.

While hundreds of samples at the small scale have been tested for shear strength in push-out tests, most large-scale tests of adhesively bonded TCC beams and slabs have a limited number of samples [12-15]. For the TTC elements, the MOE for specimens made with the wet-on-wet process at 7-days (Group E, Figure 19) and 28-day (Group F, Figure 20) were very close, and both values were significantly lower than the MOE for Group D with the dry-on-wet application method (Figure 21). However, the application method most likely did not reduce the MOE of these samples, rather the reduction in strength came from the difference in the concrete batches.

As seen in Figure 19, the samples at 7-days with the lowest strength of concrete, suffered significantly more damage to the concrete layer, with many of the sections separating. Of the 10 samples, 5 failed due to shear cracks in the concrete, followed by local shear failure in the concrete at the bond line, and the other 5 samples failed due to local crushing failure in the concrete.

In Group F (Figure 20), 1 of the 28-day wet-on-wet, specimens exhibited a severe shear crack followed by failure in the concrete at the glue line upon rebound of the wood sample. The 9 other samples failed with minor cracks in the concrete element or due to local crushing. Conversely, in the 28-day, dry-on-wet specimens, 3 exhibited a severe shear crack followed by failure in the concrete at the glue line upon rebound of the wood sample. The 7 other samples failed with minor cracks in the concrete and no local crushing failure in the concrete was seen. This suggests that at the small scale, a better bond was formed with the fresh concrete than the previously cast small-scale strips. As the compressive strength of the batch used in the wet-on-wet specimens was lower than in the dry-on-wet specimens, local crushing in the concrete was an observed failure mode in the former group and not in the latter group which all failed due to shear in the concrete element.

Figure 19: *7-day wet-on-wet MOE-MOR TCC beam specimen*

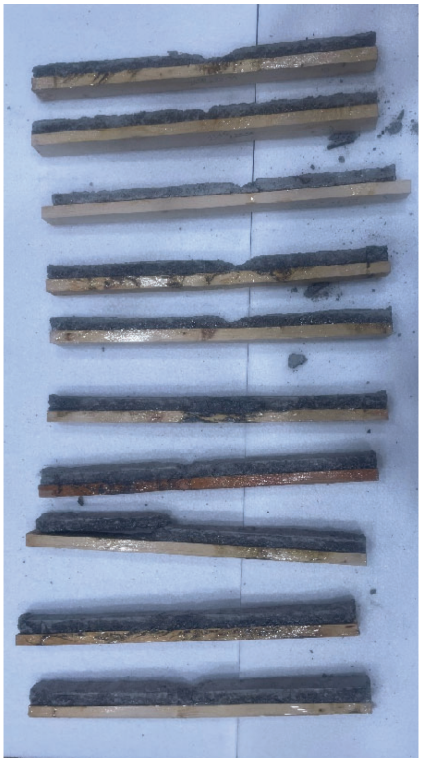

Figure 20: *28-day, wet-on-wet MOE-MOR TCC beam specimen*

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Figure 21: 28-day, dry-on-wet MOE-MOR TCC beam specimens

In compression tests, the samples with two laminae in the cross-section had an average increase in strength of 5%. The TCC columns had a compressive strength of 27.2 MPa, which was between the 46-49.7 MPa of the glulam groups and the 20.4 MPa of the concrete compression column from batch No. 1. This suggests that the adhesive bond with the wood element, with its higher compressive strength, increased the capacity of the column overall, in comparison to pure concrete columns made from the same batches of concrete. TCC compression samples consistently failed in the concrete elements as seen in Figure 22. The results show that there could be some potential in future programs studying the behaviour of prefabricated TCC wall panels.

Due to the potential for variability between wood elements, large numbers of specimens are required to increase the confidence in results, small scale testing if shown to be accurate with respect to full scale applications can allow for pilot studies to be conducted before a more expansive full scale testing program is designed.

Despite batch No. 1 and 2 of the concrete having similar compressive strength values with standard test size cylinders, the compressive strength values for batch No. 1 and 2 with small-scale compression specimens were 20.4 and 13.7 MPa, respectively. This can explain the reduction in the MOE and MOR values between the 28-day wet-on-wet specimens and the 28-day dry-on-wet specimens. To reduce the CV of the results and increase confidence of these observations, a greater number of samples are required.

Figure 22: 28-day, dry-on-wet compression specimens

5 CONCLUSIONS

Adhesive can be used to develop a perfectly rigid (full composite action) TCC structural elements. However, quality control during the adhesion application process can be an issue. Also, brittle failure modes exhibited by TCC elements that utilized adhesive for shear connections are not desirable. Using small-diameter wood species and bonding them together with an adhesive can provide mechanical properties in accurate proportion to full-size mass timber elements which have greater mechanical properties than clear wood specimens. Small scale testing of adhesively bonded TCC elements can provide informative data before large scale testing at a reduced resource cost. Small scale concrete compression tests provide a more accurate picture of the compressive behaviour of the concrete in small-scale TCC flexure beams than the results obtained from a standard size concrete tests cylinder. The quality control of the dry-on-wet application method is better due to some potential displacement of adhesive, especially at the small scale, when placing fresh concrete on top of the epoxy.

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