Investigation on the structural behaviour of timber concrete composite connections

C. Gerber & K. Crews
Faculty of Engineering, University of Technology, Sydney, Australia

D. Yeo & A. Buchanan
Faculty of Engineering, University of Canterbury, Christchurch, New Zealand

ABSTRACT: A project exploring innovative structural systems that utilise timber and provide a competitive alternative to steel and concrete products commenced at the University of Technology, Sydney, in 2007. It aims to identify and develop at least three flooring/framing concepts suitable for initial application in a two-/three-storey commercial building in Australia. In this context, a timber concrete composite (TCC) represents a competitive solution. An important aspect of TCC structures corresponds to the shear connectors, which are essential for TCC structural behaviour. Thus, they need to provide sufficient strength and impair slip between TCC layers. A laboratory investigation on these connectors is discussed in this paper. The scope and research plan are presented and the connection strength and stiffness are analysed and commented.

1 INTRODUCTION

Timber concrete composite (TCC) solutions make the most of the specific characteristics of each material, as the tensile and bending strength of the timber element and the compressive strength of the concrete slab are capitalised on. The efficiency of the shear connectors between these members is also essential in order to maximise the use of the properties of both materials.

TCC structures possess many benefits. Compared to conventional wood floor systems (joists and superimposed sheathings), they offer improved structural (ultimate and service, including vibration) and acoustic performances. Meanwhile, they are lighter than reinforced concrete structures.

This paper presents a laboratory research on TCC shear connections. The research plan and strategy are explained. The analysis focuses on the strength and stiffness of the connection. The test results are analysed (connection strength and stiffness) and discussed.

2 LITERATURE REVIEW

Whilst improvements in both structural and acoustic performance were noted, the extent of composite behaviour between the timber and concrete materials was not readily understood and engineering principles that quantified structural interactions resulting in composite behaviour between dissimilar materials needed to be developed.

Siess et al. (1952) were amongst the first researchers to undertake detailed investigations to study and quantify the composite interactions of a steel beam acting compositely with a concrete deck. Significantly, a key finding of their research was the recognition of the fact that the performance of the shear connectors was critical to achieve predictable composite behaviour between dissimilar structural materials.

It was not until the 1980's that comprehensive investigations into the performance of TCC floor systems commenced (Bletz et al. 2004) with a view to applying the technology to new structures. Subsequent research efforts led to new types of connectors being developed that made it possible during the 1990's to apply TCC systems for both floors in new buildings (Europe) and road decks on short span bridges (mainly in North America and New Zealand) (Cecotti 1995).

In Australia and New Zealand, the latest research works include a major project that has recently started at UTS (Crews et al. 2008; Crews et al. 2007) and investigations on shear connectors by Chan (2007) and O'Neill (2007).

Furthermore, in recent years there has been an increasing trend for the use of TCC systems in new buildings and construction. Two important benefits that have influenced this trend are fire resistance and low noise transfer – impact noises in particular, that have enabled timber concrete composite floor systems to meet the rigorous requirements of modern construction for multi-storey buildings.

Other benefits that have been noted (Ahmadi & Saka 1993)) include:

– lower self-weight of TCC systems relative to “equivalent” structural performance of traditional reinforced concrete structures.
– with timber elements under tension and concrete members under compression, an efficient use of the specific properties of the material is achieved.
– less prone to spalling deteriorations than steel-reinforced concrete solutions.
– favourable range of vibration responses for human comfort.

For information, a comprehensive (literature) review of shear connectors used in TCC structures – evolution from 1985 to 2004 – is available (Dias 2005). Elsewhere, Ceccotti (2002) also presents an overview of the TCC connectors which are most commonly used.

3 LABORATORY INVESTIGATION

3.1 *Scope and objective*

The scope of the subject laboratory research consists of investigating the shear strength of TCC connections. The aims are to: (a) investigate various connector types, (b) carry out a sensitivity study on slanted-facet notches, (c) deepen the understanding the performance of curved-facet notches (Chan 2007), and (d) acquire experimental reference data involving replication of test series completed at the University of Canterbury, New Zealand (O’Neill 2007).

3.2 *Detailing the test series*

The research plan has been put together in order to address the scope of this experimental work:

1. **Test reference data**: three test series which replicate three of the University of Canterbury investigation (O’Neill 2007). To this end, the timber members have been carved in three shapes – square notch of 150/25 mm* and of 300/50 mm* and 60-mm deep bird-mouth. A single coach screw (CS), 16 mm diameter and 200 mm long, is incorporated as a single type of mechanical fastener.
2. **Complementary data**: two test series which complement an experimental investigation completed at the University of Technology, Sydney (Chan 2007). The facets of the notches (170/30 mm*), carved in the wood members, are curved (S-shape). Two types of mechanical fasteners are used in these test series: a) a single coach screw (CS) (16∅ / 200 mm) and b) four wood screws (WS) (14-G / 100 mm).
3. **Sensitivity study data**: four test series which address the parameters of a sensitivity study completed with a finite element analysis. Notches of 150/30 mm* with slanted facets at 15°, 25°, 35° and 45° – have been carved into the LVL beams. The mechanical fasteners used in these test series are similar to those used for the “Complementary data” investigation.

The research plan is depicted in Figure 1:

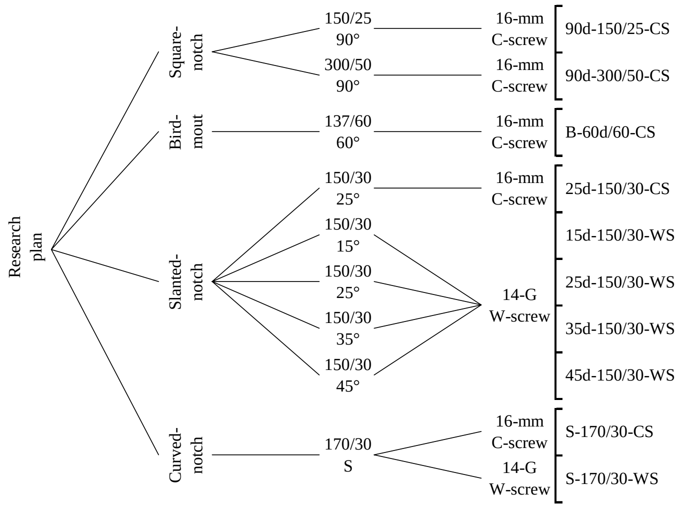

Figure 1: Research plan

3.3 *Detailing the test specimen*

The specimens have been manufactured – including the notch carving – with conventional wood hand-tools and light hand-machines, with the exception of the curve notches that have been carved with a CNC-machine.

Figure 2 depicts the specimen general dimensions. It also details the materials of the layers.

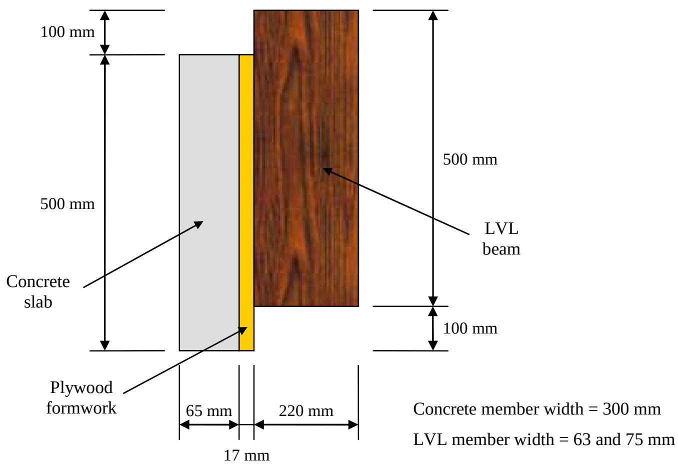

Figure 2: View of specimen – side profile.

The specific geometry of the specimen connections are detailed in Figure 3. The square notch (a) is manufactured with two different dimensions; firstly, 150 mm long and 25 mm deep and, secondly, 300 mm long and 50 mm deep. The slant notches (c) exhibit similar dimensional properties – 150 mm long and 30 mm deep – but variable angles of facet slope. The bird-mouth (b) and curved-facet (d) notches are as shown below.

* Length/depth of the notch in mm (refer to Figure 3).

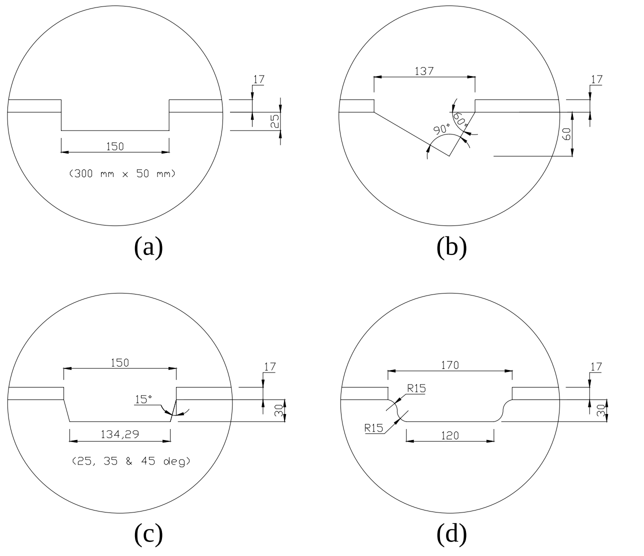

Figure 3: Detailing of the shear connections – (a) square notch (90° facets), (b) bird-mouth, (c) slant notch (15°, 25°, 35° and 45° facets) and (d) curve notch.

3.4 *Testing procedure*

All test series are conducted using a loading regime and test protocol that essentially follows EN 26891 (BSI 1991) for what is referred to as "push-out" tests. These tests were carried out with a 50-ton Shimadzu testing machine. The specimen is maintained in position with sturdy rig – all horizontal and rotational displacements are impeded. The load was introduced concentrically into interlayer in order to reduce/avoid rotational effects.

A load cell measures the applied load, whilst the relative displacement between the members of the specimens is recorded as follows:

- Two Linear Variable Differential Transducers (LVDT) measure the slip between the plywood member and the timber beam.
- One LVDT measures the slip between the concrete member and the timber beam.
- One LVDT monitors the travel of the cross-head of the testing machine.

The loading regime is regulated by the loading speed (timed phase) and the load intensity which is represented schematically in Figure 4. It comprises five main phases:

1. The load is applied until about 40% of the failure. This stage is normally completed in about two minutes.
2. The load is maintained at this intensity (about 40% of the failure) for about 30 seconds.
3. The load is released until about 10% of the failure. This stage aims to last about one and a half minute.
4. The load is maintained at about 10% of the failure for some 30 seconds.
5. The load is (re-)applied until failure of the specimen. The speed of the load input aims to match that of the first stage.

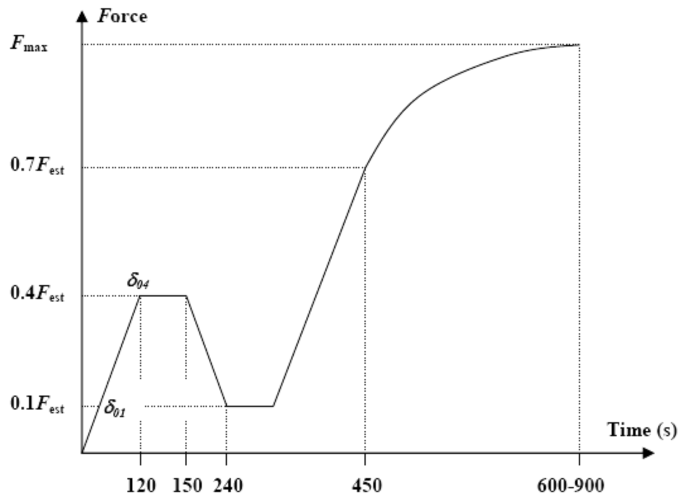

Figure 4: Loading regime as per EN 26891 (BSI 1991).

Note: Because the testing machine is governed by the load exclusively, instead of the time, some variation to the loading regime can be expected.

4 TEST RESULTS

4.1 *Analysis of the loading regime*

A graphical analysis demonstrating that loading regimes, as required in EN 26891 (BSI 1991), were achieved is shown in Figure 5. Whilst this graph also indicates some measure of variation between the experimental and the EN-26891 loading regime, it is however within an acceptable range.

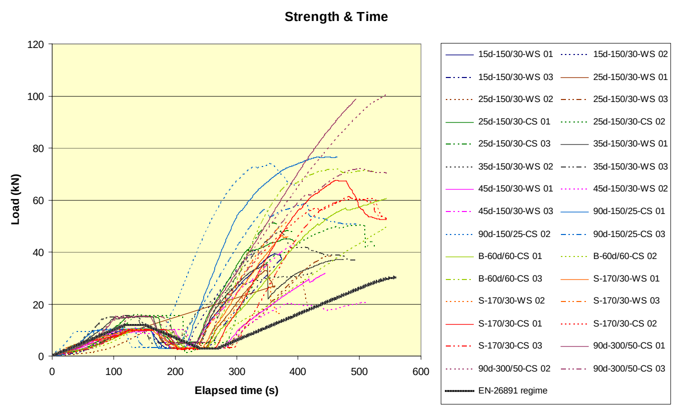

Figure 5: Analysis of Loading Regime with respect to time

4.2 *Analysis of the connection strength*

The strength of the reference test series – 90d-150/25-CS and B-60d/60-CS – can be considered to be within the range of the results obtained by O'Neill (2007). The variation observed is believed to be attributable to the manufacturing and material properties/characteristics of the specimens of the subject investigation. Furthermore, 90d-300/50-CS series delivered very high strength, 92.5 kN (no comparative data available in O'Neil) – strength 1.5

to 3.0 times higher than the other test series of this research.

Analysis of results from series S-170/30-WS and S-170/30-CS, indicates significant losses of strength when compared to Chan's results (2007), with observed reductions of 46% and 23% respectively. A construction detail of the specimen which introduced intermediary formwork integrated into the TCC assembly (not previously present), is considered to be the main cause of this variation, due to the fact that it has introduced a point of significant shear concentration at a critical location and as a result the plywood interlayer increased the eccentricity in the connection. Furthermore, the size and shape of the hole carved in the plywood may also generate a concentration of shear stress at unwanted locations of the connection.

It should also be noted that the subject and Chan investigations incorporated different types of mechanical fasteners; nail-plates and wood screws in Chan's investigation (2007) and wood and coach screws in the subject test series. These connectors have inherently dissimilar structural behaviour in terms of both embedment strength in the wood and interlocking/shear transfer with the concrete.

Table 1: Strength of the specimens.

Series name & Specimen number		Maximum load (kN)		Standard deviation	Coefficient of variation	Comment	Target load (kN)
90d-150/25-CS	01	76.60	68.98	10.98	15.9%		71.8*
	02	73.95					
	03	56.40				58.65 kN	
B-60d/60-CS	01	61.25	66.48	5.38	8.1%		82.6*
	02	66.20					
	03	72.00					
90d-300/50-CS	01	105.00	92.45	17.78	19.2%		no data available
	02	100.25					
	03	72.10					
S-170/30-WS	01	46.35	44.35	8.33	18.8%		81.8†
	02	35.20					
	03	51.50					
S-170/30-CS	01	67.60	63.15	3.86	6.1%		81.8†
	02	60.70					
	03	61.15					
15d-150/30-WS	01	39.40	40.00	1.97	4.9%		no data available
	02	42.20					
	03	38.40					
25d-150/30-WS	01	33.00	34.05	4.03	11.8%		no data available
	02	30.65					
	03	38.50					
25d-150/30-CS	01	45.12	49.01	3.39	6.9%		no data available
	02	50.55					
	03	51.35					
35d-150/30-WS	01	35.45	38.33	8.31	21.7%	37.25 kN	no data available
	02	31.85					
	03	47.70					
45d-150/30-WS	01	32.20	31.67	11.26	35.6%		no data available
	02	20.15					
	03	42.65					
Source: *O'Neil (2007), †Chan (2007).							

The specimens of the sensitivity study – 15d-150/30-WS, 25d-150/30-WS, 35d-150/30-WS and 45d-150/30-WS – exhibit medium strength in comparison with the reference test series, ranging from 46% to 58% of 90d-150/25-CS strength. Arguably a direct comparison is distorted to some extent by the incorporation of dissimilar mechanical fasteners used in these connections. However, comparing the 90d-150/25-CS and 25d-150/30-CS indicates that the latter only reaches 71% of the reference 90d-150/25-CS strength.

Two specimens; one in each of the 90d-300/50-CS and 45d-150/30-WS specimen series vary significantly from the other results and could arguably qualify as outliers. Examination of both specimens revealed that air bubbles remained trapped in the concrete. This indicates that these specimens may have insufficient compaction during concreting. Without outliers, 90d-300/50-CS and 45d-150/30-WS series exhibit a sharply lower variation of 3.3% (-15.9%) and 19.7% (-15.9%) respectively.

The strength performance of the specimens is summarised in Table 1.

A comparison of relative strength of each of the connection types is presented graphically in Figure 6 (coach and wood screws are labelled as CS's and WS's in the specimen name respectively), where the strength of each connection is expressed as a percentage of the strength achieved for the strongest connection (90d-150/25-CS)* – which corresponds to 100%. It can be clearly seen that the connections with a CS achieve higher strength than that with those WS's.

Furthermore, two distinct groups of performance bands can be identified; the first one includes 90d-150/25-CS, B-60d/60-CS and S-170/30-CS (these three series offering high strength), whilst the second one includes the slanted-facet connection, with these series achieving about 50% of the strength of 90d-150/25-CS.

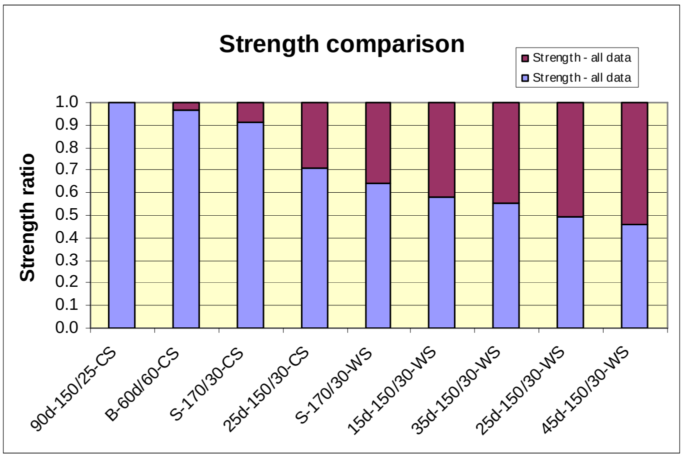

Figure 6: Strength comparison of the connections.

Observation of failures in the WS-specimen indicates that the length of screws provided insufficient embedment into the concrete. Typically, these connections experience brittle shear failure, which consistently occurred in a plane coinciding with the top of the screws, as can be seen in Figure 7.

* The 90d-300/50-CS series is not considered in this study because its construction parameters – size of the notch – are significantly different to that of the other test series of the research plan.

Figure 7: Failure of a specimen with wood screws.

A sensitivity study of the experimental results (Figure 8) indicates that the correlation between the slope of the notch facet and the strength of the connection is poor. As such, it would appear that identifying an optimal slope for the facet of the notch is not readily unachievable using the experimental outcomes of these tests. These mitigated results may be linked to the plywood formwork: (a) it introduces an extra layer and (b) the carving in the plywood has a 90° facet (generating unfavourable peak of stress).

Furthermore, it is evident from the failures seen in Figure 7 that the mechanical fasteners used in these tests (wood screws) failed to achieve satisfactory interlocking with the concrete slab and achieve adequate reinforcement of the connections.

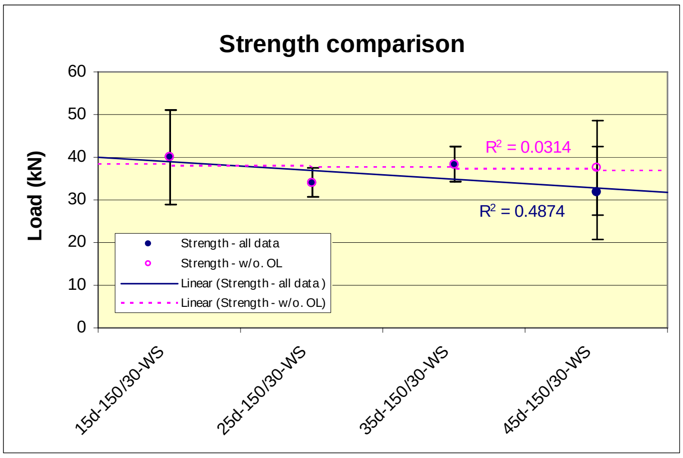

Figure 8: Strength comparison of the connections – sensitivity study.

4.3 *Analysis of the connection stiffness*

The stiffness for each of the connections has been derived from the load versus relative slip between the concrete slab and the LVL beam, by performing a regression analysis of the test data where the specimen demonstrates linear load-versus-slip characteristics. This assessment indicates that the stiffness properties of each type of connection are similar, with the exception of the 90d-300/50-CS series whose dimensions are significantly different to the other series. Details of this analysis are summarised in Table 2.

Two sets of data are presented in this Table – the numbers in Bold indicate the stiffness derived considering the relative displacement between the concrete and the beam. For the numbers not in Bold the stiffness was approximated using the displacement of the cross-head of the testing machine – which is less accurate because the displacement includes the overhead travel resulting in an apparent lower stiffness.

This analysis also suggests that, unlike the strength characteristics and failure modes, the mechanical fastener appears to have little influence on the connection stiffness. For example, 25d-150/30-CS and 25d-150/30-WS series exhibit quasi equal stiffness characteristics. This could indicate that for serviceability behaviour in the linear elastic range, the stiffness of the connection is essentially governed by interaction occurring at the notch facet between the concrete and the timber.

This analysis seems to confirm as well – as identified in Section 4.2, that one specimen of 90d-300/50-CS and 45d-150/30-WS test series are outliers. Conducting the examination without these outliers, the variations of 90d-300/50-CS and 45d-150/30-WS series become 14.4% and 3.7% respectively.

Table 2: Stiffness of the specimens.

Series name & Specimen number		Stiffness (kN/mm)				Standard deviation		Coefficient of variation	
	01	35.55	*27.02*						
15d-150/30-WS	02	38.44	*28.99*	**35.13**	*26.08*	**3.54**	*3.47*	**10.1%**	*13.3%*
	03	31.40	*22.24*						
	01	33.57	*22.18*						
25d-150/30-WS	02	35.49	*18.26*	**32.82**	*19.53*	**3.12**	*2.29*	**9.5%**	*11.7%*
	03	29.39	*18.16*						
	01	29.29	*26.09*						
25d-150/30-CS	02	27.60	*25.02*	**32.71**	*27.62*	**7.43**	*3.62*	**22.7%**	*13.1%*
	03	41.24	*31.75*						
	01	ND	*23.04*						
35d-150/30-WS	02	ND	*28.60*	**ND**	*26.68*	**ND**	*3.15*	**ND**	*11.8%*
	03	ND	*28.39*						
	01	39.75	*28.35*						
45d-150/30-WS	02	33.31	*21.94*	**36.50**	*25.73*	**3.22**	*3.36*	**8.8%**	*13.1%*
	03	36.45	*26.89*						
	01	55.47	*34.88*						
90d-150/25-CS	02	46.26	*36.67*	**50.86**	*33.57*	**6.51**	*3.92*	**12.8%**	*11.7%*
	03	ND	*29.17*						
	01	34.89	*27.31*						
B-60d/60-CS	02	32.67	*19.52*	**34.71**	*26.09*	**1.96**	*6.05*	**5.6%**	*23.2%*
	03	36.57	*31.44*						
	01	32.63	*25.67*						
S-170/30-WS	02	34.82	*23.94*	**34.04**	*24.74*	**1.22**	*0.87*	**3.6%**	*3.5%*
	03	34.67	*24.62*						
	01	40.09	*29.06*						
S-170/30-CS	02	34.73	*27.46*	**36.85**	*28.52*	**2.86**	*0.91*	**7.7%**	*3.2%*
	03	35.72	*29.03*						
	01	75.70	*43.87*						
90d-300/50-CS	02	61.94	*35.75*	**60.15**	*39.55*	**16.51**	*4.08*	**27.4%**	*10.3%*
	03	42.83	*39.03*						

NOTE: stiffness derived with the load and the cross-head travel of the testing machine.

A relative comparison of each connection stiffness with respect to the stiffest connection (90d-150/25-CS)* as shown in Figure 9 indicates that all of the test series specimens demonstrate stiffness

* Refer to Section 4.2.

characteristics which are about 65% of that of 90d-150/25-CS.

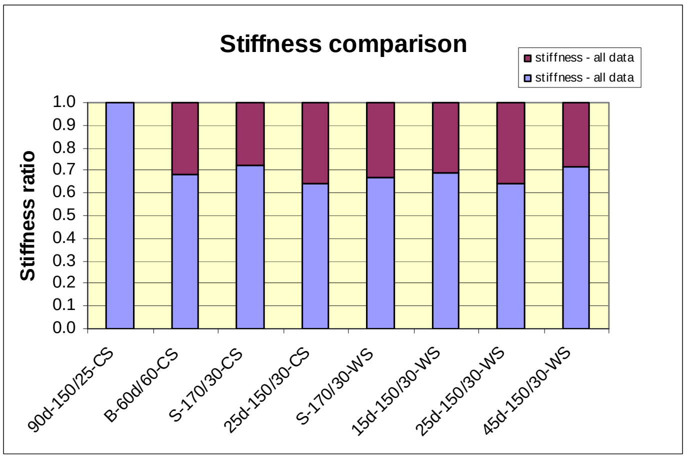

Figure 9: Stiffness comparison of the connections.

5 CONCLUDING COMMENTS

The results of the investigation presented in this paper have considerably increased the understanding of the behaviour of timber concrete composite (TCC) connections.

Despite the fact that the expected results were not achieved and in some instances, the strength was lower than anticipated, this investigation has enabled the collection of important and critical data, especially in identifying the influence of the plywood formwork layer on the shear performance of the TCC connections. Most of the specimens with wood screws (WS's) suffered "premature" failure, whereby each of them exhibited a similar failure mode, where shear fracture occurred in a plane coinciding with the heads of the screws.

The mediocre performance of the two "outlier" specimens highlights the importance of ensuring that the compaction process is undertaken carefully to ensure consistent quality in fabrication of the concrete notch connections. For optimal connection performance, the compacting needs to be sufficient in order for the concrete to flow into the notch cavity with adequate density, whilst at the same time it must not be excessive in order to avoid segregation by concentrating the larger aggregates in the lower zone of the concrete slab.

The sensitivity study has disallowed to draw any recommendation with regard to the slope of a notch with slanted facets. The construction of the specimen – (additional) plywood interlayer and WS's as mechanical connectors (inadequate length) – is anticipated to have some influence in the outcome of this aspect of the investigation.

The test results also highlighted the need for further investigations about the influence of a plywood interlayer, particularly where the edges of the plywood formwork are in close proximity to the notch carved in the beam. Further testing and a Finite Element model – currently under development – are planned to address this issue.

6 ACKNOWLEDGEMENT

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