BENDING TESTS ON TIMBER CONCRETE COMPOSITES WITH PERFOBOND CONNECTIONS

Elif Appavuravther[1], Bram Vandoren[1], José Henriques[1]

ABSTRACT: Long spans in timber concrete composites (TCC) is the next step of improvement that is ambitioned by the industry and designers for more efficient structures. With Perfobond connections, which are originally developed for steel-concrete composites (SCC) constructions, targeting longer spans in TCC is feasible. In this paper, full scale TCC beams are experimentally investigated under four point bending with the use of Perfobond connections. Two sets of experiments are performed with a variation of the concrete type (normal weight concrete vs lightweight concrete). The results indicate that the use of Perfobond connections lead to a linear behaviour until initial local damage. In specimens with lightweight concrete, failure in the most loaded connections is observed, however it did not lead to strength degradation. For specimens with normal weight concrete however, maximum load is obtained with the connection failure which led to significant cracking of timber under bending (tension side) and subsequently, the collapse of the TCC beam. As a result of this experimental campaign, a performant behaviour of the TCC beam implementing the Perfobond connections is observed and therefore, longer spans may be envisaged.

KEYWORDS: Perfobond connector, adhesively bonded connection, timber concrete composite, bending test

1 INTRODUCTION

The use of timber is re-gaining popularity in the construction sector. To comply with the neutral emission regulations in Europe by 2050, the use of timber is one of the solutions that can help since the carbon emission of the wood is much lower when compared to the traditional, commonly used construction materials, such as concrete. To overcome the weaknesses of the structural properties of using bare timber, such as vibration and deflection, the combination of concrete with timber is an innovative solution which is becoming more and more implemented by the construction sector. Besides its reliable structural behaviour, using a concrete slab and timber beam allows a prefabricated solution where the on-site application time can be limited, the quality of the materials and assembly can be controlled due to limited execution on site. Concrete can also be used to rehabilitate and reinforce the existing timber structures. Timber-concrete composite solutions are relatively new and the experimental work on bending behaviour of the beams is limited in the current literature [1, 2].

In a TCC beam, the target is that the concrete slab resists the compression stresses and the timber beam resists the tensile stresses. This optimal case can be obtained once the beam is in a high composite action. Such high composite action is obtained with connections with high stiffness. Traditional connections used in TCC, such as dowel connections, are limited in strength and stiffness [3, 4]. Notch connections lead to a high strength and stiffness, however they do not prevent an uplift (and therefore use of a screw is required) and have a very brittle behaviour [5, 6]. Bonded-in connection is another solution to overcome the limitations on strength and stiffness exhibited by common dowel connections [7]. Even though these connections have been investigated for decades, only recently researchers are coming to an agreement to have requirements in the design codes, such as a sub-section dedicated to bonded-in rods in the version under preparation of the prEN 1995-1-1 [8]. This is an important step to support designers using bonded-in solutions however, it only covers steel rods, and an extension to steel plate connectors is still to be done since they are being experimentally investigated in TCC for the past few decades [9-15].

Once the connection behaviour is determined, it is important to examine the behaviour of the connection in full scale composite beams under bending loading. The bending tests helps to determine how the composite action is achieved, how efficient it is, the distribution of stresses, the impact of the connection behaviour on the mechanical performance of the beam and therefore the capacity to distribute load.

In this work, Perfobond connections commonly used in SCC are adopted into TCC beams. Perfobond is a steel plate connector, originally developed for SCC beams. The steel plate, welded to the steel beam, is embedded in the concrete slab where mechanical interlock is mobilised at

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the tip of the plate and through a concrete dowel action, obtained through predrilled holes in the plate [16], simultaneously, shear-slip and uplift resistance are mobilised.

In this experimental work, two different configurations are tested, one series with normal weight concrete and one with lightweight concrete. Failure loads and failure modes are compared for the two cases. The results indicate that, with the use different concrete types and strengths, similar behaviour and load capacity are obtained. Then, given the high strength and stiffness of this connection, leading to increased spacing between connectors, the suitability of the Gamma method to predict bending stiffness and load capacity is assessed. Moreover, experimental results are compared with more common solutions, such as rod connections from the literature, to further evaluate on the performance of TCC beams using Perfobond connections. The results show potential for the development of long spans beams.

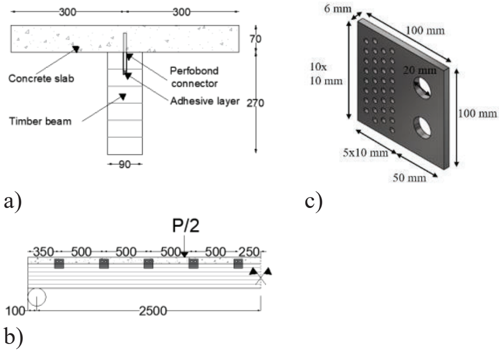
2 MATERIALS AND METHODS

2.1 TEST SPECIMENS AND DESIGN

In this study, full scale bending tests are performed on 5.2 m long TCC beams. Three replicas of each series are tested. The difference between the two series is the concrete type. The concrete slab cross section was 600 x 70 mm and timber with a cross section of 90 x 270 mm (see Figure 1 (a)). In the timber beams, ten grooves with the dimensions of 110 mm x 55 mm x 10 mm are opened. For each beam, a total of ten connections are used, with spacing of 500 mm. The locations of the connections are presented in Figure 1 (b). The spacing is determined using the Gamma method for residential building and complying to ultimate limit state and service limit state [17].

The timber beam is covered by an adhesive tape to avoid moisture flow from the concrete to the timber and to avoid the friction between the two materials. The adhesive, with approximately 2mm thickness, is applied and dried in an indoor environment and following the recommendations given in the product Technical Documentation [18].

Additionally, a bare timber beam with the same cross-section as those used in the composite solution was tested for sake of comparison.



a)

c)

b)

Figure 1 *Test specimens (a) cross section of the TCC beam (b) elevation view of test specimens (c) Perfobond connector dimensions*

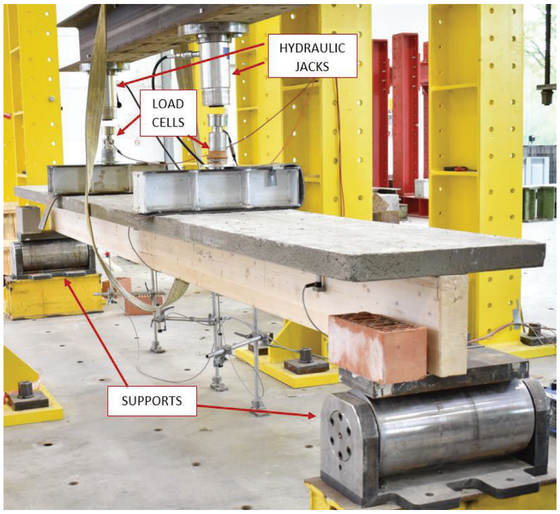
2.2 MATERIALS

In the specimens denoted with P-NWC, normal weight concrete with a 28- day cubic compression strength of 41 MPa and density of 2200 kg/m^3 is used. In the series denoted by P-LWC, lightweight concrete with a 28- day cubic strength of 25 MPa and density of 1600 kg/m^3 is used. Minimum reinforcement is used to avoid concrete tension cracks [19]. Glulam timber of strength class 24h (Picea Abies specie) is used. Perfobond connectors with steel grade S355 are used, with cross section dimensions given in Figure 1 (c). The Perfobond is designed using the design model given in the literature [16]. For the bonding between the Perfobond connector and the timber beam, Sika Anchorfix-3030 epoxy-acrylate is used [20].

2.3 TEST SET-UP, MONITORING AND TEST PROCEDURE

The experimental set-up consists of a meccano system (the experimental frame), a hydraulic jack, load cells, supports and LVDTs (Linear Variable Differential Trasformer), as illustrated in Figure 2 (a). In total, eight LVDTs are installed on each beam, seven in the horizontal direction and one in the vertical direction at the midspan. The horizontal ones correspond to either connection location or placed under the loading. The LVDT locations are given in Figure 2 (b).

Each specimen was centred both in longitudinal and transversal direction to avoid eccentricity due to loading. The loading protocol given in EN 26891 is followed [21].



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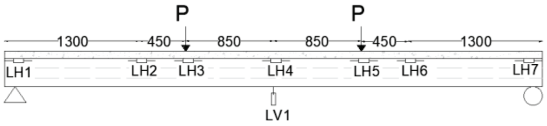

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Figure 2 *(a) Test set-up (b) LVDT Locations*

3 RESULTS AND DISCUSSION

3.1 TEST RESULTS

In Figure 3, the force-midspan deflection behaviour of all three replicas of each series and of the bare timber beam under four point bending is given. In Table 1, mean loads, at two different load levels, are given, i) at the initial failure, F_1, where the first failure is observed (during the experiments with the change in the slope of the force-slip behaviour) and ii) the maximum load where sudden loss of resistance is observed, $F_{\max}$.

For the P-NWC series, no initial failure load is recorded as the first peak in the load lead to sudden load decrease.

A steep linear behaviour is obtained until $F_{\max}$ and the recorded force is 67.6 kN on average. At this point, the failure is due to the connection failure. In Figure 4 (a), the slip increase at $F_{\max}$ can be observed for specimen P-NWC-A (for force-slip behaviour of the beams, only the results of one series is presented for sake of clarity and as other specimens followed a similar trend). The major slip increase occurred at the LH1 and LH2 followed by LH3. The LVDT LH2 is located approximately under the third connection (see Figure 1 (b)), which justifies the connections 1, 2 and 3 failing, causing the significant slip measured at LH1 and LH2. Because of the brittleness of the connection in this case (with this type of concrete, NWC), the redistribution of force does not occur smoothly. The load was distributed among the connections as there are a few spikes of increase in load after a drop, as the slip increases, until the load could no longer be bore by the timber beam. A picture of the failed beam can be found in Figure 5 (a) where the timber failure is clear. Minor cracks at the concrete were observed however, failure of the connections was not extended to a visible form in the concrete and timber.

For the P-LWC series, a very steep behaviour is observed until on average 55.8 kN. At this point, a reduction in the slope of the force-deflection is observed without loss of the load capacity. At this load level, F_1, cracks around the connections are observed. The slip recordings from LH 1 and 2 given in Figure 4 (b), show the first three failed connections. A significant slip increase is recorded on LH 3 and 5 where the 4th connection is located showing that also failure on those connections occurred. The load is distributed among the remaining connections until the load capacity increased on average of 66.2 kN and at this load level, timber cracked, as given in Figure 5 (b), setting to the maximum capacity of these specimens. At the maximum load, the cracks around the connections became more visible and cone shaped failures are observed as the connection rotated with the increased load (see Figure 5 (b & c)). And this behaviour is different from the previous, here, connection failed in a less brittle mode which is seen by the fact that load is still increasing in a smooth way up to maximum load. It should also be noted that no uplifting occurred between the concrete and the timber layer.

One timber beam (90 x 270 mm) is tested under the same conditions to observe the difference with the TCC beams. A linear but rather more flexible behaviour is observed. The beam failed due to bending strength (tension) at 44.8 kN. This force-deflection curve clearly shows how the use of concrete improves the strength and stiffness of a timber beam.

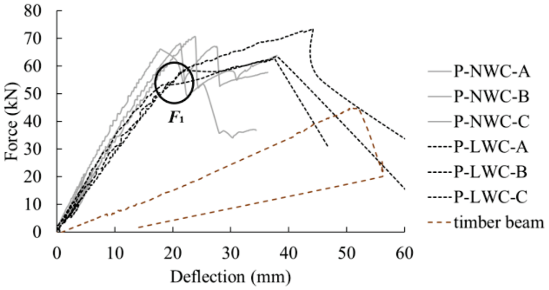
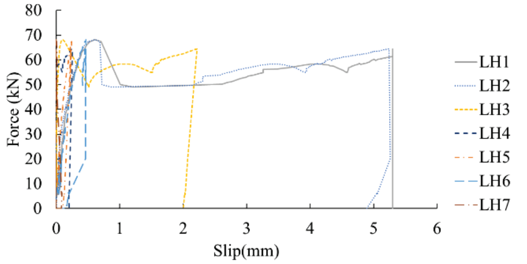


Figure 3 *Force-midspan deflection*

Table 1 *Experimental results (failure loads and failure modes)*

Specimen ID	F_1 (kN)	$F_{\max}$ (kN)	Failure at F_1	Global failure
Timber beam	-	44.8	-	Timber tension failure due to bending
P-NWC	-	67.6	-	Connection failure
P-LWC	55.8	66.2	Connection failure	Timber tension failure due to bending



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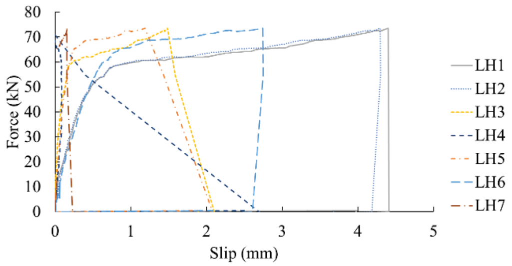

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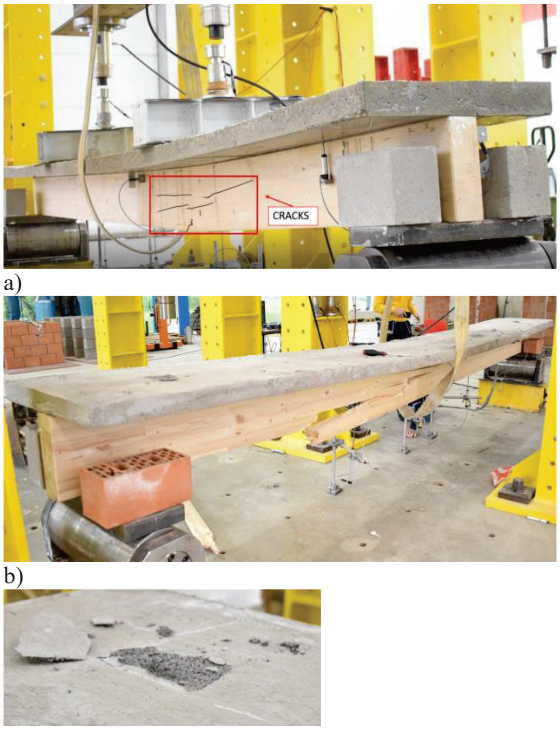
Figure 4 *Force-slip curve (a) P-NWC-A (b) P-LWC-C*



a)

b)

c)

Figure 5 *Failed specimens (a) P-NWC (b) P-LWC (c) P-LWC first connection failure resulting in cone failure in the concrete due to rotation of the connection*

3.2 DISCUSSION

With the change in the type and the strength of the concrete, a few observations can be made;

- The stiffness the TCC beam (Figure 3) is not significantly affected. The use of normal weight concrete lead only to a slightly stiffer behaviour. This increase is due to higher young modulus of this concrete type and of corresponding connection stiffness [22].
- The concrete type had an impact on the pre-peak behaviour due to the different behaviour of the connection with each type. In NWC the connection is stronger but more brittle not allowing a smooth distribution of forces through the connections distributed along the beam.
- As concrete did not govern maximum load capacity, the two series presented similar load capacity governed by the cracking of the timber beam. However, the concrete type played a role in the pre-peak behaviour due the impact of the concrete type at the shear connection level [22].
- The use of concrete and shear connections lead to 24% and 50% increase on load capacity with lightweight concrete and normal weight concrete, respectively.
- The curve (Figure 3) shows a significant difference in the bending stiffness between the composite beams and the bare timber. The bending stiffness increased 3.2 and 2.6 times when normal weight concrete and lightweight concrete and connections are added to the bare timber, respectively.

4 APPLICATION OF THE GAMMA METHOD TO A DISCRETE CONNECTION

Currently, the Gamma method is the analytical approach used for design since it is in the design code prEN 1995-1-1 [17]. Even though the limited range of application can lead to deviations on the prediction of the bending stiffness of the composite beam, and the corresponding stress distribution [23], the method is commonly used due to the simplicity and suitability for the current practical applications of TCC beams. Some of the causes of such deviations is in the fact that the model is developed for sinusoidal loading and the load distribution among connections is assumed to be equal. This assumption is accurate if the connection spacing is small [1]. In this work, however, with four-point bending and connection spacing of 500 mm, this is not the case. The connections outside in the loading zones does have same shear flow, however, the slip is higher further away from the midspan. The slip results showed that not all connections failed at the same load level (specially the series P-NWC – the decrease and increase in the force-deflection curve shows the connections failed gradually).

In Table 2, the comparison of experimental results with the Gamma method are given for the bending stiffness (EI), maximum load ($F_{\max}$) and failure modes. In addition to experiments from this paper, an example from the literature with rod connections are used [23].

The expected failure mode by the Gamma method was the connection failure for the Perfobond connections, and combined bending and axial forces for the rod connections [23], which are in agreement with the experimental results reported. The connection forces are calculated using prEN 1995-1-1 Annex B [17].

The results show in terms of maximum load prediction, 33% and 62% underestimation is recorded for normal weight and lightweight concrete, respectively. The force limit for connections is introduced from the shear test results [22]. In shear tests, for the series with the use of lightweight concrete, failure at the connection level is recorded at less than half in comparison to the series with the normal weight concrete. This justifies the 100% difference in the expected failure loads. This results clearly show that in the Gamma method, the connection forces are underestimated under bending behaviour. And 21% of underestimation is recorded from the rod connection Again, this underestimation is due to the fact that with the Gamma method, linear force distribution among all connections is assumed, whereas, in this study and the literature [23], it is shown that it does not represent the reality and the underestimation of connection forces. The spacing of connections is however, is expected to cause more deviation, which is also shown in this comparison.

With the Perfobond connections the overestimation of bending stiffness is approximately 5%, however for rod connection this is limited to 13%. The limited deviation for these experiments shows a good accuracy however, overestimation can cause problems in design applications. With bending stiffness, the results are in better agreement with the Gamma method as it is directly dependent on the mechanical and geometric properties of the composite beams.

***Table 2** Bending stiffness comparison between experimental results and Gamma method using Annex B of EN 1995-1-1 [17]*

	EI (kNm^2)	**F_{max} (kN)**	**F_{max} mode**
P-NWC	8285.7	67.6	Connection failure
P-NWC_ Gamma method	8703.0	45.3	Connection failure
Difference (%)	-5.0	33.0	
P-LWC	7161.7	55.8	Connection failure
P-LWC_ Gamma method	7613.5	21.5	Connection failure
Difference (%)	-6.3	61.5	
Sebastian et al. [23]	1889.8	40.0	Combined bending and axial force
Sebastian et al._Gamma method	1638.2	31.6	Combined bending and axial force
Difference (%)	13.3	21.0	-

5 CONCLUSIONS

The objective of this work is to investigate the bending behaviour of TCC beams incorporating Perfobond shear connections. As a result of this experimental work, it can be concluded that Perfobond connections lead to a strong behaviour under bending loading. In both series, where the difference was the strength and the type of the concrete, the initial failure was a connection failure, followed by a bending strength (timber tension) failure.

The results indicate that the concrete type and strength had an effect on the load-deflection behaviour of the beam as it impacted the connection behaviour, however, maximum load capacity was not very different since the failure was due to the timber.

When the force midspan deflection of the TCC beam is compared with a (non-composite) timber beam, an increase of 24% and 50% on load capacity with lightweight concrete and normal weight concrete, respectively was recorded.

With the use of the Gamma method from prEN 1995-1-1, the bending stiffness, expected failure load and failure mode are compared. The results show that even though the failure mode was in agreement, Gamma method underestimates the maximum load and overestimates the bending stiffness. The deviation in bending stiffness can be explained with the deviation in the material properties. The deviation in the maximum load capacity depends on a few factors such as loading type, connection spacing and underestimation of the connection forces under bending loads.

This work shows that, with the given parameters, high composite action can be obtained with connection failure, which is targeted in TCC. Especially when lightweight concrete is used, controlled ductile failure is recorded.

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