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Comparative study on the failure of TCC and BCC: A review

* S.T. Deresa[1)] and J.J. Xu [2)]

[1), 2)] *College of Civil Engineering, Nanjing Tech University, Nanjing 211816, P.R. China*
[1)] simtes2009@gmiail.com

ABSTRACT

Sustainability is now becoming a major concern in the modern construction industry. Despite being a major economic sector, the construction industry is causing adverse environmental impact. To this end, special attention should be paid to the selection of more "green" construction materials for structural applications. Therefore, a reasonable choice of construction materials can be made on the bases of acceptable structural performance, economic benefits, and sustainability. For instance, the use of composite beams made with traditional concrete and bio-based materials (such as timber and bamboo) is a valuable solution. Timber-Concrete Composite (TCC) beams have been used for decades in various structural applications such as new buildings, refurbishment of old timber structures, and bridges with several environmental benefits. Recently, different researchers proposed composite beams similar to TCC ones but based on engineered bamboo commonly named Bamboo-Concrete Composite (BCC) beams. This study presents comparison of the failure mode of the TCC and BCC beams udder four-point bending test. In particular, TCCs beams are compared with BCC ones considering similar shear connectors.

1. INTRODUCTION

Timber-concrete composite has been recognized as a solution to economical construction by minimize the disadvantage of timber and improving its utilization in structural applications. The optimized benefit of the two materials in a composite system can only be realized through an effective shear connector that links the concrete to timber. Extensive researches were done on various connectors to evaluate the strength and stiffness properties of the connection system and were able to obtain structurally efficient composite system. Studies have also been extended to different types of timber products such as lumber as a timber, laminated veneer lumber (LVL), Cross laminated timber (CLT) and nail laminated timber (NLT) to make a composite system. However, less attention has been paid to sustainable construction practices as yet. Sustainable construction is becoming a major concern in today’s construction industry. To secure sustainable construction practice, it demands a special attention to be paid to the selection of construction materials. Compared with other building materials (e.g., steel, timber and concrete), bamboo has the following merits for engineering application: *i*)

[1)] Ph.D Student
[2)] Associate Professor

shorter growth cycle; *ii*) lower thermal conductivity; *iii*) lower energy consumption; *iv*) higher strength-to-weight ratio; *v*) easy for prefabrication and assemblage (Xiao et al., 2013b; Sharma et al., 2015); and for these reasons, it is very promising to extend the application of engineered bamboo in structural applications. Glued laminated bamboo, namely glubam, is an engineered bamboo developed by Xiao et al. (Xiao et al., 2007). Recently, a series of experiments are, (Xiao et al., 2010; Xiao et al., 2013a; Xiao et al., 2017), carried out to investigate the material properties and structural performances of glubam. Following these studies, glubam has been used in bridges structures. Similar to timber-concrete composite floor system (Ceccotti, 2002; Clouston et al., 2004; Dias, 2005),

A reasonable choice of construction material can, therefore, be made on the bases of structural performance, sustainability and economic benefits. Thus, the comparison of structural performance of the timber-concrete composite (TCC) and the bamboo-based composite, bamboo-concrete composite (BCC) system is very crucial. It allows to make a wise decision on selection of construction materials for structural application. Therefore, this paper presents comparison of mechanical and structural performances of bamboo-based composites with timber-concrete composite (TCC), based on the global and local behavior of the composite.

2. Comparison of bending Performance of TCC and BCC

(Shan et al., 2020) and (Deresa et al., 2019) conducted bending test on full-scale bamboo-concrete composite beams using glubam beams replacing the timber beam . Shan *et al*. (Shan et al., 2020) conducted bending test on 8000 mm bamboo-concrete composite (BCC) using 112 mm × 380 mm (width × depth) glubam beam (glubam from thin bamboo strips) and 900 × 100 mm (width × depth) concrete using various shear connectors. Similarly, (Deresa et al., 2019) conducted a bending test on 3600 mm long composite beam made of glubam (from thick bamboo strips) and recycled aggregate concrete (RAC) slab. The bamboo-recycled aggregate concrete composite (BRACC) or glubam-recycled aggregate concrete composite (GRACC) is composed of a glubam joist of 60 mm × 300 mm (width × depth) and recycled aggregate concrete flange of 1000 mm × 100 mm (width × depth) connected using screw and notch shear connectors. The RAC slab is manufactured with 30% recycled aggregate (RA) replacing the natural aggregate (NA). This percentage was chosen based on research findings from literatures on the effect of recycled aggregate for structural applications. Accordingly, up to 30% replacement of RA don't significantly affect the compressive strength and structural performance of concrete.

A number of researches have been conducted to study the structural performance of timber-concrete composite system through bending test using various types of shear connectors. Among these studies some recent ones are considered herein to compare the local and global failure behavior, and the overall structural performance of the bamboo-concrete composites to the TCC system. Studies are chosen based on the type of shear connectors used in the composite system. Therefore, the bending test result of these composite systems with the same connection type ($i.e.$ notch and screw shear connectors) are selected for comparison. Accordingly, (Yeoh et al., 2009a) conducted bending test on timber-concrete composite. The LVL joist has 63 mm width and 400 mm height while the concrete slab is 600 mm wide and 65 mm depth with 17 mm plywood under the concrete slab. The notch length in in LVL-concrete composites is 150 mm and 300 mm. (Van der Linden, 1999) conducted bending test on TCC beams of each 5700 mm long constructed from glulam as timber beam and concrete slab made of concrete grade C-25. Three types of shear connectors were used including notch reinforced with dowels of Ø20 mm and screw arranged inclined at ± 45°. The timber beam was 100 mm tick and 200mm deep, while the concrete slab was 70 mm thick and 600 mm wide. (Gutkowski et al., 2008) conducted bending test on layered timber-concrete composite of rectangular cress-section using notch shear connector reinforced with dowels. The bending test specimens had a span of 3510 mm with two types of cross-sectional configurations: i) concrete slab size of 305 mm × 64mm, and timber beam size of 305 mm × 89 mm: ii) concrete slab size of 267 mm × 64 mm, and timber beam size of 267 mm × 89 mm. (Quang Mai et al., 2018) conducted a full scale bending test on cross-laminated timber-concrete (CLT) composite using different types of shear connectors. Five specimens of rectangular cross-section with size of 900 mm ×6000 mm (width × length) with 150 mm depth of timber and100 mm depth of concrete topping were tested. Shear connectors of Ø10 mm coach screw and Ø7.5 mm SFS with length of 180 mm and 145mm, respectively, were used at different orientations ($i.e.$ ± 45° and 90°). (Derikvand et al., 2019) experimentally investigated the bending capacity of TCC system made of nail laminated timber (NLT) and concrete under short term bending test using Ø7.4 mm and 145 mm long SFS screw inclined at 45° as shear connector.

2.1 Comparison of the failure mode

Figure 1 presents pictures showing the failure mode of the timber-concrete and GRAC composites. (Yeoh et al., 2009a) reported two types of failure mode for the notch connection: *i*) for is under-designed connection, composite beams showed connection failure due to shear or crushing of concrete with plasticization of the coach screw in the notch: *ii*) for the well-designed connection, the global failure of the composite system is essentially attributed to tensile failure of the LVL joist in the constant bending zone. (Gutkowski et al., 2008) reported failure mode that can entirely characterized as initial flexural tensile failure of the timber beam in the span with the maximum moment region. The study findings presented herein indicate that the global failure of the TCC system with a sufficiently designed notch shear connector (reinforced with either screw or dowels) is essentially attributed to the tensile fracture of the timber joist in the span between the two loading points.

In a similar fashion, (Deresa et al., 2019) reported that the final failure of BRAC composite beams with the notch shear connector is exclusively characterized as flexural tensile failure of the glubam. The failure phenomenon observed can be explained that the glubam beam failed in tensile fracture and the bamboo strips pulled-off. In addition, shearing of the glubam due to delamination cracking that extended from the base of the last notch to one end was also observed. By contrast, (Shan et al., 2020) reported that the global failure of the BCC is attributed to the connection failure for specimens with the notch series with inclined cracking of concrete and plasticization of screw in the notch. As can be seen from **Figure 1**, concrete crushing inside the notch due to shear has occurred in both composite systems. However, extent of the concrete damage is somehow larger in the TCC system. It should be noted that the connection system in the BRACC is designed in such a way that it has to provide sufficient strength so that there should be no connection failure during the collapse test. Indeed, the failure observed indicted that the required condition was met. The notch adopted in the BRAC composite is cut inclined at 15^0 from the vertical. The inclination angle is supposed to provides advantage to avoid the stress concentration of a right angle at the base of the notch and proper placement of concrete during casting of the slab (Gutkowski et al., 2008).

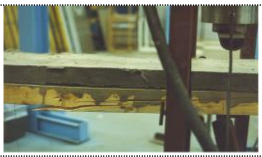
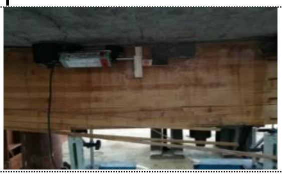
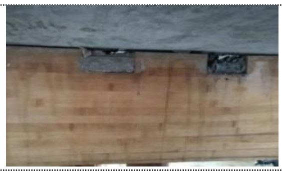
(Yeoh et al., 2009a)		
	a) Tensile failure of the LVL beam	b) Concrete crushing in the notch
(Gutkowski et al., 2008)		
	a) Tensile failure of the timber beam	b) Concrete crushing in the notch
(Shan et al., 2020)		
	a) Connection failure, screw plasticization in the notch	b) Concrete crushing in the notch
(Deresa et al., 2019)		
	a) Tensile failure of the glubam beam	b) Concrete crushing in the notch

Figure 1. Failure pattern of the composite beams (Picture taken from the respective literatures)

(Van der Linden, 1999) reported similar failure mode for the composites with both the notch and screw connectors. Firstly, concrete cracks observed in maximum tension zone with further widening and development of additional cracks upon increasing the load. Secondly, a gap between the timber beam and concrete slab occurred at location near the support, at one end. The gap increased as the load increased. After this, for the notch connection, the timber beam split at the notch near the last connector at one end. Shear block failure of the concrete in notch is also noticed which is described as a failure similar to that of ring and shear-plate connection in timber to timber connections. Finally, the global failure of the composite beams, with both the screw and notch shear connectors, is governed by the tensile failure of the timber beam. Similarly, the failure phenomena of timber-concrete composite system presented by Lukaszewska et al. (Lukaszewska et al., 2010) with screw connection also characterized as typical tensile fracture of the timber joist. (Lukaszewska et al., 2010) highlighted that no apparent damage was observed on screw, but the wood around the connector showed minor signs of embedment failure. (Quang Mai et al., 2018) reported a combined tensile and shearing type of failure. The tensile failure occurs at the lower part on the first layer of the timber while shearing happened at the interface of the laminate at the maximum moment zone. As the load increased, shearing due to delamination at the interface of each layer subsequently progressed to the next transverse layer. It is mentioned that there was no significant failure observed in the concrete slab except few hairline cracks in the maximum moment zone. (Derikvand et al., 2019) also reported essentially tensile failure of the timber beam leading to the global failure of composite beams.

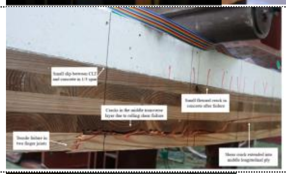
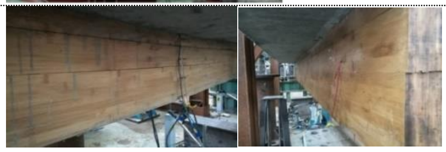
(Lukaszewska et al., 2010)		Failure of the timber joist, SC-1-L
(Quang Mai et al., 2018)		Failure of the timber joist
(Deresa et al., 2019)		Sheared type of failure of glubam beam for Screw connection
Shan *et al*. (Shan et al., 2020)		Sheared type of failure of glubam beam for Screw connection

Figure 2. Failure of the composites with screw connections

On the other hand, the Bamboo-concrete composite beams with screw shear connecter showed a different type of failure mode from the TCC system. The global failure observed in both the BCC and BRAC composites with screw connection is somehow similar and can, exclusively, be characterized as sheared type of failure due to the delamination cracking of the bamboo strips in the glubam sheet. **Figure 2** shows some representative samples of failure mode of timber-concrete composite reported in the cited literatures, and bamboo-concrete composite beams with screw shear connector.

3. CONCLUSIONS

The failure mode of specimen with notch shear connector can be exclusively attributed to the tensile failure of the joist for both the TCC and BCC system given that the connection system is well-designed.

BCC with screw shear connecter exhibited different type of failure mode from the TCC system with an exclusively sheared type of failure due to the delamination cracking of the bamboo strips in the glubam sheet.

The use of recycled aggregate in the concrete slab has showed no effect in the failure mode of the composite as the failure of all composite in the BRACC system is attributed to the failure of the glubam beam.

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