Stiffness and Strength Degradation of Timber Concrete Composite under Fatigue Loading

Kevin J.T Yeo¹ and David E.C Yeoh¹

¹ Jamilus Research Centre, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA
Corresponding author: david@uthm.edu.my

Abstract. The design of TCC is often associated with Gamma Method to calculate its effective stiffness as its characteristic strength to predict its SLS and ULS behavior. TCC structures used as bridges are subjected to fatigue loadings during service life. Fatigue loadings causes degradation of strength and softening of TCC structure. Such effect produces damaging consequences on the concrete, timber and especially the shear connectors. The effective stiffness degradation of the TCC structure subjected to fatigue loading within SLS and beyond SLS are studied due to scarcity of past researches on the fatigue behavior of TCC structures. This research was carried out by utilizing Malaysian tropical timber (Koompasialamalaccensis) where its strength properties was tested according to ASTM D198 standard procedures. Not much significant changes of its effective stiffness and connection stiffness is observed when subjected to fatigue loadings within SLS but the degradation process occurs at an instantaneous rate when subjected to fatigue loading beyond SLS. The S-N curve, strain profile and post-mortem analysis generated provides a summarization and indicative prediction for the fatigue life behaviour of the designed TCC.

1. Introduction

TCC structures can be used as an alternative solution to Industrial Building System (IBS) for building floor system and short bridges across monsoon drains for pedestrian and light vehicles instead of steel or reinforced concrete. In general, the concrete layer in TCC structure is designed to resist compression and bending while the timber part resists the tension and bending with the shear force transferred through the connectors [1]. However, the technology of TCC is still new in Malaysia and many researches are required to understand the structural behaviour of TCC structures. The continuous growth of interest in TCC has sparked an interest in its fatigue behaviour. To date, the body of knowledge in the fatigue behaviour of TCC is still not well established due to the scarcity of experimental test data [2].

Fatigue loading is generated by recurring force such as mechanical system, moving traffic or equipment testing on the structure. Hence, fatigue is a state where the material is weakened when fatigue load is applied which leads to microstructural changes. A S-N curve for a particular structural component relates a prescribed number of cycles (N) within a nominal, usually constant magnitude or applied stress range (S) where the component can safely withstand [3]. The S-N curve has been a fundamental of mate-rail fatigue studies. It not only functions for characterizing fatigue test results but also serve for predicting the fatigue life of the structure or material which involves fatigue damage and stress ratio effect [4].

The fatigue loading imposed on the structure is often complicated in reality. Hence, it is easier to look at constant values while studying the principles of fatigue behaviour as real load conditions are
difficult to replicate [5]. Depending on the applied stress level, there are many types of fatigue test such as:

- Short-life test: Stress level are designated above SLS of the specimen and some specimens are expected to fail statically.
- Long-life test: Stress level are chosen below SLS of the specimen so that it does not fail after a preassigned number of cycles.

Under some circumstances, complex sequences with varying maximum stress amplitudes are probably required [3].

The present study is aim at conducting a fatigue test by utilizing Malaysian tropical timber- Kempas in the TCC structure to investigate its stiffness and strength degradation when subjected to fatigue loading within SLS (low amplitude) and beyond SLS (high amplitude). The research begins with the preliminary testing of materials such as concrete, shear connectors and the Kempas timber according to ASTM D198 standard procedures so that their strength properties can be applied in the Gamma Method for the design of TCC deck specimen. The S-N Curve derived from experimental results will provide an approximation value on how the stiffness and strength deteriorate under increasing numbers of fatigue loading.

2. Experimental Investigations

Gamma Method is commonly used in the design of TCC structures. In the Gamma method, a reduction factor known as shear coefficients, $\gamma$ is introduced to measure the degree of interaction from the concrete slab. The value $\gamma$ ranges from 0 representing no interaction between timber and concrete to 1 signifying full composite action. Preliminary testing for the properties and characteristic strength of timber, concrete and shear connectors are required to be applied in the Gamma Method [6]. The fatigue test of the TCC slab deck will be proceeded once it was designed from the Gamma Method where the effective stiffness and maximum moment resistance was determined.

2.1. Preliminary Testing of Materials

Since Malaysia is known for producing good quality tropical timber, the resources of Malaysia timber should be widely utilized. Kempas (Koompasia malaccensis) is chosen among a wide variety of tropical timber in Malaysia because of its good characteristic strength and is very suitable to be used as structural timber in construction. The properties testing for Kempas timber such as tensile test, compression test and bending test was done according to the procedures of ASTM D198 where the tensile test specimens have a special tensile grip area and neck-down shape configuration to determine its tensile strength [7].

The stress-strain graph is determined to identify their respective strength properties. Concrete that achieved an average strength of 35MPa was used throughout the experiment. In this experimental research, screws are used as shear connectors as they are simple to install, easily available and high load-bearing capacity. The screws have 70mm long, 7mm in diameter and the spacing between the thread of the screw is 2mm. The push-out test was continued with increasing laminations of timber so that the strength of the shear connectors for the TCC deck can be determined. The results obtained are applied in the Gamma Method for the design of TCC deck.

2.2. Experimental Setup for Fatigue Test

There are 3 TCC specimens constructed for the fatigue test of TCC structure so that an S-N Curve can be obtained. The designed TCC specimens have a span of 3.6m and a total of 10 shear connectors are used for the TCC structure with unequal spacing because the shear force at the edge of the structure is bigger. Figure 1 shows the plan view of the TCC structure while Figure 2 shows the front view of the TCC structure. Figure 3 shows the TCC specimens placed under the actuator for fatigue test.
In Figure 1 and 2, the spacing of shear connectors at the end-span of TCC is smaller because more shear connectors are needed there to provide a better composite action compared to the midspan. In Figure 3, three Linear Variable Differential Transducer (LVDT) was situated at the surrounding of the TCC specimen. One is located at the midspan to detect its midspan deflection and the other two was at the edge of the concrete layer and the timber layer respectively to detect the slip difference of the TCC specimen. The back-to-back C channel act as a spreader beam for the applied loading during the experimental testing. Strain gauges are also attached to the TCC specimens during the fatigue test. Figure 4, 5 and 6 shows the position of strain gauges attached to the TCC specimen to observe the stress distribution that occurs in the TCC.
2.3. Load Protocol for the Fatigue Test

From the TCC specimens constructed, two samples are taken for fatigue loading and one are tested for its actual load bearing capacity. The two samples undergo sinusoidal cycles of fatigue loadings with the frequency of 1 Hz. The amplitude of the fatigue loadings will be different for both specimens with the first one at 10kN minimum and 20kN maximum (within SLS) and the other at 60kN minimum and 120kN maximum (beyond SLS). The low amplitude fatigue loadings are to emulate pedestrian (7km/h) and light vehicle movements (15km/h) while crossing the designed TCC deck.

The load protocol begins with 10 slow cycles with a frequency of 0.1 Hz to obtain a slope in the load-displacement graph where its stiffness after a prescribe number of cycles is obtained from the gradient of the slope. The time required for the TCC specimen to undergo the number of pre-scribe cycles of fatigue loadings can be a very long process. The timing for the prescribed number of cycles required to complete must be estimated and planned out carefully to avoid the actuator from functioning during weekends and public holidays for supervision convenience and preventing over heating of actuator machine. The low amplitude fatigue loading was chosen to be at 10 to 20kN to emulate pedestrian and light vehicles crossing situation It was expected that as the number of fatigue loadings in sinusoidal cycles increases, the degradation of connection stiffness and structural stiffness of TCC will also increase which results in the decrease in load bearing capacity of the TCC deck.

3. Results and Discussions

3.1. Results of Preliminary Testing of Materials

The Kempas timber was tested for its compressive strength, tensile strength and bending strength parallel to grain so that its values can be applied in the Gamma Method. Table 1 below shows the tabulation of results obtained from the preliminary testing of Kempas timber.

| Strength Properties (N/mm²) | Specimen 1 | Specimen 2 | Specimen 3 | Average |
|-----------------------------|------------|------------|------------|---------|
| Compressive Strength, L=200mm | 87.3       | 87.7       | 85.8       | 86.9, (1.1%) |
| Compressive Strength, L=100mm | 91.2       | 92.4       | 95.0       | 93.3, (2.1%) |
| Tensile Strength            | 105.3      | 114.9      | 104.4      | 108.7, (5.4%) |
| Bending Strength             | 256.4      | 170.6      | 189.7      | 205.6, (21.9%) |

Note: Coefficient of Variation (CoV) is given in brackets

From the experimental testing, consistent results are obtained particularly in the compression test and tensile test with a coefficient of variation of 2.1% and 5.4% which means a very low variability in results. For the compression test, it was observed that the specimen with length, L=100mm has an average higher compressive strength than the specimen with length, L=200mm as the latter specimen is slenderer with the same cross section. During the compression test, most of the specimens failed because of the splitting of the timber fibres. Whereas snapping of the timber fibres in the necking part of the
specimen occurred in the tensile test. The bending strength of the Kempas timber is very much higher than the tensile and compressive partly because the size of timber specimen (1200mm x 90mm x 40mm) is bigger than the tensile and compressive test specimen with an effective span of 950mm. Hence, there are more timber fibres to support the load. Although the bending strength of the timber is very high, there is still a variance up to 86 N/mm\(^2\) and a 21.9% coefficient of variation due to the fact that timber is a biological material. The tensile test and compression test can achieve more consistent results than the bending due to the smaller size of specimen where the defects and quality of the timber is easier to control. The properties of concrete were tested to ensure it achieve an average strength of 35 MPa in the TCC specimens. Table 2 summarizes the tabulated results for concrete compression test.

### Table 2: Compressive strength of concrete after 28 days hydration period

| Cube | Compressive Strength (N/mm\(^2\)) |
|------|----------------------------------|
| 1    | 35.7                             |
| 2    | 32.8                             |
| 3    | 34.2                             |
| Average | 34.2                   |

In overall, Table 2 shows consistent results were obtained in the compression test of concrete. On the other hand, the study of the structural performance of shear connectors is classified as another broad range of study in the field of TCC. The strength of the shear connector signifies the maximum load capacity of the specimen while its stiffness is characterized by \((K_s)\) for SLS and \((K_u)\) for ULS which is determined by the secant slip moduli of the maximum load achieved by the specimen in the load-displacement graph at 40% and 60% of its maximum load capacity respectively. Table 3 shows the tabulated results of the push-out test.

### Table 3: Values for the properties of shear connectors from experimental push out test

| Number of timber(s) | Connection Stiffness for Serviceability (kN/mm), \(K_s\) | Connection Stiffness for Ultimate (kN/mm), \(K_u\) | Characteristic Strength of Connection (kN), \(f_k\) |
|---------------------|------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1                   | 12.8                                                 | 11.7                                          | 5.3                                           |
| 5                   | 17.4                                                 | 14.0                                          | 12.0                                          |
| 10                  | 24.1                                                 | 32.1                                          | 53.5                                          |
| 20                  | 44.0                                                 | 45.0                                          | 65.0                                          |

The properties of shear connectors were tested with increasing laminations of timber until 10 and 20 was derived theoretically as the specimen would be too big to be fitted in the push-out test machine. The results obtained from preliminary testing are applied to the Gamma Method for the design of TCC deck specimens. From the Gamma Method, the designed TCC only has a concrete coefficient, \(\gamma_1\) of 0.52 which suggest it is not a very good composite action in the concrete layer. The designed TCC has an effective stiffness, \(E_{I\text{eff}}\) of 5.557 x 1012 N/mm\(^2\) for SLS and 5.601 x 1012 N/mm\(^2\) for ULS. It was predicted that the TCC structure has a maximum moment resistance of 300kNm which is equivalent to a point load of 330kN. However, when the load is increased to a point 183kN, the concrete layer will fail first and eventually the timber part at ultimate load.

### 3.2. Results of Fatigue Test

The experiment starts with the TCC specimen subjected to low amplitude fatigue loadings of 10 to 20kN until 1 million cycles. The effective stiffness degradation was determined from the gradient of load-displacement graph generated by the 10 slows cycles in the load protocol before the proceeding with the prescribed cycles of fatigue loading. Figure 7 summarizes the effective stiffness degradation for the TCC structure subjected to fatigue loadings within SLS in S-N Graph.
From results of Figure 7, it can be seen that there is a minor amount of stiffness degradation that occurs in the TCC structure when subjected to fatigue loadings within SLS as it completed the total prescribed 1 million cycles of fatigue loading. Slight increase in the effective stiffness was also observed due to the yielding stage of shear connectors during the fatigue loading process. Figure 8 shows the connection stiffness degradation of TCC deck subjected to fatigue loading within SLS in the S-N graph where the connection stiffness is measured by the gradient of the load-slip difference between the timber and concrete tabulated on the load-slip difference graph.

From the results in Figure 8, the connection stiffness degradation for fatigue loadings within SLS is more noticeable compared to the effective stiffness degradation. This phenomenon can be explained with the shear connectors installed in the TCC system has a low yielding strength. From past research on the fatigue behaviour of steel, it was claimed that steel with a higher yield strength has a better performance in fatigue compared to steel with lower yielding strength as their fatigue crack growth rates was compared during the research [8]. As a result, the shear connectors in the TCC deck showed signs of yielding during the early stages of the fatigue loading cycles and its connection stiffness gradually decreases as the fatigue loading in sinusoidal cycles continued. The early yielding and connection stiffness degradation subsequently affects the effective stiffness degradation of the TCC structure but at trivial manner. The overall TCC structure successfully withstand even after subjected to 1 million sinusoidal cycles of fatigue loadings within SLS.

The following TCC specimen was subjected to fatigue loadings beyond SLS where the fatigue loadings were increased to 60kN and 120kN. The fatigue behaviour in terms of stiffness degradation of the TCC when subjected to fatigue loadings beyond SLS occurs at a very instantaneous rate. This situation is observable due to the frequent triggering from the actuator as a sudden and steep increase of midspan deflection was detected while fatigue loadings is applied. Figure 9 shows the effective stiffness degradation of TCC when subjected to fatigue loadings beyond SLS tabulated in the S-N graph and Figure 10 shows the comparison of effective stiffness degradation when subjected to fatigue loadings within SLS and beyond SLS.
From the results in Figure 9 and its comparison in Figure 10, it was observed that a steep change in effective stiffness occurs almost immediately when the TCC structure is subjected to fatigue loadings beyond SLS and there is not much of significant changes in stiffness when the TCC structure is subjected to fatigue loadings within SLS even when 1 million sinusoidal cycles of fatigue loadings was completed. This condition can be explained from the perspective of Gamma Method as it can predict the maximum load capacity of the TCC structure. The fatigue loading up to 120kN may be only 40% of the maximum load capacity of the TCC structure but it was almost 70% of the failure load at the concrete layer and also 80% for the shear connectors at the TCC structure. Hence, before the time the TCC reached 6900 cycles of fatigue loading, the concrete layer had already failed and was separated from the timber due to damage of the shear connectors, leaving only the timber to support all the applied loadings and the concrete self-weight. A sharper increase of stiffness degradation was observed at the latter stage of S-N graph when the TCC structure subjected to fatigue loading beyond SLS as it was mainly the stiffness degradation of the Kempas timber. Consequently, there is no need to continue the fatigue loading test as there is already no composite action in the structure. Figure 11 shows the S-N graph for the connection stiffness degradation of TCC deck subjected to fatigue loadings beyond SLS.
From Figure 11, a polynomial curve equation seems to have a better fitting in the results for the connection stiffness degradation of TCC when subjected to fatigue loadings beyond SLS. This is due to the yielding that occurs in the shear connectors. The yielding of the shear connectors would cause the connection stiffness to increase. This leads to an increase in the composite action of the TCC where the timber would displace outwards due to tension and the concrete to displace inwards due to compression when subjected to the loading. The changes of displacement for both components caused an increased gradient in the graph. When the shear connectors break after the yielding, the composite action for the TCC decreases. Hence, both components are displaced outwards due to the tension force which causes the difference of displacement to decrease when the fatigue loading is applied. Resultantly, the gradient of the load-slip difference graph decreases.

3.3. Results of bending test after fatigue loading
Since there is a decrease in the effective stiffness in the TCC structure after subjected to fatigue loading, the maximum load capacity of the TCC structure also decreases. Table 4 shows the comparison of effective stiffness obtained from the Gamma Method calculation with the experimental results. Figure 12 shows the load-displacement graph obtained from the bending test of all the TCC specimens constructed for the fatigue test.

| TCC Specimen                     | Effective Stiffness (kN/mm) | Accuracy (%)   |
|----------------------------------|-----------------------------|----------------|
| Gamma Method Bending (without fatigue) | 5.0852                      | 92%, 8% overestimation |
| Fatigue within SLS (initial)     | 5.4419                      | 97%, 3% underestimation |
| Fatigue beyond SLS (initial)     | 5.8833                      | 94%, 6% underestimation |

From the results in Table 4 and Figure 12, this research shows good accuracy of the Gamma Method in determining the effective stiffness of the TCC structure up to 90% and also the relationship of the effective stiffness degradation when subjected to fatigue loadings with its load bearing capacity. From the load-displacement graph, the TCC specimen with no fatigue loadings subjected shows higher stiffness while comparing with the other 2 specimens but have a lower maximum load capacity compared to the specimen subjected fatigue loadings within SLS. This reason is due to timber is a biological material and its quality and strength properties is diverse. Similar pattern of results was shown in past researches and also preliminary testing. Therefore, it was not necessary to discuss further on the bending strength of the TCC specimen without fatigue loadings on it as it did not support the hypothesis of this research. Since there is an insignificant amount of effective stiffness degradation that occurs in the TCC specimen subjected to fatigue loadings within SLS, there is not much changes in the load bearing capacity (300kN) when compared with the prediction in the Gamma Method (330kN). For the TCC
specimen that was subjected to fatigue loadings beyond SLS, the effective stiffness was greatly reduced due to damage in the concrete and shear connectors, leaving the Kempas timber part to support the fatigue loadings and the concrete self-weight. Resultantly, the TCC specimen subjected to fatigue loading beyond SLS reaches its ultimate limit state (ULS) when loaded up to 130kN. The bending test results also showed the good elastic properties of the Kempas timber in the TCC structure in the load displacement graph in figure 20 as it recovers from the deflection at ULS once the loading was removed. Figure 13 shows the S-N graph generated for comparison of TCC structures load capacity.

Figure 13: S-N graph for comparison of TCC load capacity

Due to the in-consistency in bending strength of the Kempas timber with a 21.9% coefficient of variation in the preliminary testing, the bending strength of the TCC specimen without fatigue loading did not achieve the desired load capacity as predicted in the Gamma Method. Hence, the value calculated from the Gamma Method was used in the S-N graph shown in Figure 13 as the quality and defects of solid timber (Kempas) is difficult to control when applied in a structural scale specimen. The S-N graph generated provide a stark contrast comparison in the load bearing capacity of TCC structure when subjected to fatigue loading with SLS and beyond SLS.

3.4. Strain Profile Comparison

The strain profile which shows the stress distribution that occurred in the TCC structure was tabulated to support the findings in the fatigue test results and also the hypothesis of the research. The strain profile was emphasized during the bending test of the specimens after subjected to different amplitudes of fatigue loadings. From there, different composite action for each of the TCC specimen was observed. Figure 14 and 15 shows the tabulated strain profile at the midspan of TCC deck for fatigue loadings within SLS and beyond SLS.

Figure 14: Strain profile at midspan of TCC with fatigue within SLS
Figure 15: Strain profile at midspan of TCC with fatigue beyond SLS

By comparing Figure 14 and 15, the TCC deck after subjecting to fatigue loading within SLS still has a better composite action during the bending test compared to the TCC deck subjected to fatigue loading beyond SLS. This is due to the shear connectors is still intact in the TCC deck thus still capable of transferring the shear force to the timber part making the concrete part more exposed to compression zone while the timber is more exposed to the tension zone. Contrarily, most of the shear connectors in the TCC deck subjected to fatigue loading beyond SLS was already broken and unable to transfer the shear force from the concrete component to the Kempas timber. Hence, no composite action was observed in its strain profile in Figure 15 as both of the concrete and timber component was subjected to compression and tension zone equally. For both of the strain profile tabulated in Figure 14 and 15, both of the specimens were compared at the load level of 10kN, 20kN, 60kN and 120kN without its load level at ULS because the strain value at ULS load level is too large and would make the earlier mentioned load levels looked insignificant and difficult to compare when tabulated together.

3.5. Results of Post-Mortem Analysis

During post-mortem analysis, the concrete layer of the TCC is hacked away to observe the conditions of the shear connectors after fatigue loadings and bending test. Any deformations or breaking of shear connectors in the TCC specimens were recorded. Table 5 and Table 6 shows the tabulated condition of shear connectors where broken shear connectors are marked with an ‘X’ while ‘90’ suggests that the shear connectors are still in good condition without any deformations. Any value below 90 suggest the degree of bending for the shear connectors.

From the observations in Table 5, not much of damage of shear connectors is observed for TCC specimen subjected to fatigue loadings within SLS with most of the shear connectors still being in good condition. In Table 5, some slight deformations only occurred at the endspan of the TCC structure as the shear force in a uniformly distributed loading is usually larger. Since the fatigue loading within SLS does minimal damage to the shear connectors, there is still composite action in the TCC structure as shown in the strain profile which enables it to have a higher effective stiffness and load-bearing capacity compared to the TCC specimen subjected to fatigue loadings beyond SLS in Table 6. The damage of shear connectors in the TCC specimen subjected to fatigue loadings beyond SLS are more severe. All the shear connectors at the endspan were already broken or deformed, leaving only the 6th row of shear connectors which is situated at the midspan of TCC in good condition. This is mainly because the shear force at the midspan is usually minimal for a uniformly distributed load. The findings in the post-mortem analysis showed good agreement with the fatigue test results and the strain profile tabulated because most of the shear connectors subjected to fatigue loading beyond SLS were destroyed which resulted in a lower composite action, resulting a lower effective stiffness and load-bearing capacity.
### Table 5: Condition of shear connectors for fatigue loading within SLS

| Number of Rows | 1st row of connectors | 2nd row of connectors | 3rd row of connectors | 4th row of connectors | 5th row of connectors | 6th row of connectors | 7th row of connectors | 8th row of connectors | 9th row of connectors | 10th row of connectors |
|----------------|-----------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|------------------------|
| 1              | 80                    | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 2              | 80                    | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 3              | X                     | 90                     | 90                    | X                     | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 4              | 80                    | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 5              | 80                    | X                      | 90                     | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 6              | 80                    | 90                     | X                      | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 7              | X                     | 90                     | X                      | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 8              | X                     | X                      | 90                     | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 9              | 80                    | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 10             | X                     | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 11             | X                     | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 12             | X                     | 90                     | 90                    | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 13             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 14             | X                     | 90                     | X                      | 80                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 15             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 16             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 17             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 18             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 19             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |
| 20             | X                     | 90                     | X                      | 90                    | 90                    | 90                    | X                     | 90                    | 90                     | 90                     |

### Table 6: Condition of shear connectors for fatigue loading beyond SLS

| Number of Rows | 1st row of connectors | 2nd row of connectors | 3rd row of connectors | 4th row of connectors | 5th row of connectors | 6th row of connectors | 7th row of connectors | 8th row of connectors | 9th row of connectors | 10th row of connectors |
|----------------|-----------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1              | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 2              | 40                    | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 3              | X                     | X                      | X                     | X                     | X                     | 90                    | 90                    | 90                    | 90                    | X                     |
| 4              | 40                    | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 5              | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 6              | 50                    | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 7              | 50                    | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 8              | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 9              | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 10             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 11             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 12             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 13             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 14             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 15             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 16             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 17             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 18             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 19             | X                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 90                    | X                     |
| 20             | 40                    | 50                     | X                      | X                     | X                     | 90                    | 90                    | 90                    | 90                    | 80                    |

X: Shear connectors are present and in good condition.
4. Conclusion
Based on the experimental results presented on this paper, the following conclusion are deduced:

- The Gamma Method is capable of determining the effective stiffness of the designed TCC structure up to 90% of accuracy.
- The results from the preliminary testing of timber especially in the bending test showed the bending strength of timber has high coefficient of variation because the defects and quality of the solid timber in a structural scale is more difficult to control. Hence, the material properties are based on average results from the specimens tested.
- In overall, the research showed good accuracy in showing the stiffness and strength degradation of TCC structures when subjected to fatigue loadings. The effective stiffness of TCC and its shear connectors does not change significantly when subjected to fatigue loadings within SLS. The effective stiffness of TCC structure and its shear connectors will decrease rapidly when subjected to fatigue loadings beyond SLS because the loadings could possibly be near to the failure load of the concrete layer and shear connectors.
- The TCC technology combines the timber and concrete elements using shear connectors to achieve a better stiffness and higher load bearing capacity but it is still not a homogenous material where the timber, concrete and shear connectors still have their own failure load.
- Aside from fulfilling the objectives of the research which focus on the fatigue behaviour of TCC structure, this paper also provides an overview on what can be improved in future researches such as overcoming the inconsistency of Malaysian tropical timber and a more effective utilization by post-processing it to engineered timber before being used as structural materials.

5. References

[1] Yeoh, D, Fragiacomo M and Carradine D 2013 Fatigue behaviour of timber–concrete composite connections and floor beams Engineering Structures 56 2240-2248
[2] Balogh J and Atadero R 2013 Fatigue testing of wood-concrete composite beams Technical Report (United States: Mountain Plains Consortium) pp 1-24
[3] Zhu H 2014 Experimental Investigations of Residual and Fatigue Capacities of Timber Connections with Glued-In FRP Rods PhD Thesis (Vancouver: University of British Columbia)
[4] Burhan I and Kim H 2018 SN curve models for composite materials characterisation: An evaluative review Journal of Composites Science 2(38) 1-29
[5] Lokken, N. (2016). Fatigue of threaded rods subjected axial load Master Thesis (Oslo: Norwegian University of Science and Technology)
[6] Zhang C 2013 Analysis of the Timber-Concrete Composite Systems with Ductile Connection PhD Thesis (Toronto: University of Toronto)
[7] Ahmad Z, Bon Y C and Abd Wahab E S 2010 Tensile strength properties of tropical hardwoods in structural size testing. International Journal of Basic and Applied Sciences 10(03) 1-6
[8] Carvalho D, Silva A L L, Jesus A M P and Fernandes A A 2015 Fatigue behaviour of structural steels comparison of strain life and fatigue crack propagation data Mecanica Experimental 25 67-78