



Pilot Study on the Vibration Behavior of TCC Laminated Deck Systems

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Abstract: The timber concrete composite (TCC) deck system is a new technology that consists of timber and concrete composite structures but remains uncommon in Malaysia. TCC is a structural system where timber beams and concrete slabs are combined to form a composite material, resisting tensile stress and compressive stress, respectively. The addition of concrete slabs protects timber beams from direct contact with water, which is crucial to ensure the durability of timber beams. Different types of connectors can be used to provide force exchange between concrete slabs and timber beams. This research was conducted to study the vibration behavior of timber-concrete composite deck systems with or without concrete topping. The deck was constructed using twenty pieces of sawn timber measuring 3.6m x 0.09 m with a concrete topping of 0.065m. Experimental tests were conducted using an electrodynamic shaker with a frequency range of 1 Hz to 200 Hz. The shaker was placed on a laminated deck as vertical force and 15 accelerometers were used as output data collectors. Me'scope and SAP2000 package were used for data analysis. The natural frequency values of the first mode shape with and without concrete topping based on Me'scope analysis are 12.8Hz and 16.9Hz, respectively. Meanwhile, the finite element modeling analysis shows that the frequency of the first mode shape with laminated deck without concrete topping is 11.4 Hz while the one with concrete topping is 16.2 Hz. The natural frequencies obtained from the experimental test and the modal analysis are greater than 8 Hz, thereby concluding that the TCC laminated deck system is suitable and comfortable for building occupants.

Keywords: TCC, vibration behavior, mode shape

1. Introduction

Timber-concrete composite (TCC) floor is a combination of timber deck and concrete topping which is widely used in Europe both in new and existing buildings. The combined strength of these elements can be enhanced by adding connectors to the side as a binder in the slab. The best properties of concrete and timber can be exploited because bending and tensile forces induced by gravity loads are resisted primarily by timber whereas compression can be resisted by concrete [1]. Thus, awareness of vibration behavior and design methods of TCC is important for this type of construction in the building industry. Timber concrete composite floors have more advantages than ordinary floors in terms of strength and durability [2]. Furthermore, the TCC floor structure has lower deflection value but has the ability to bear and withstand higher loads. This is the main reason that this structure is used to replace historic wooden flooring [1]. With the existence of TCC technology, reduction in the use of concrete is possible, along with cost and

construction time. Wastage in the use of concrete, especially during the repair work of the building structures, can also be avoided.

The design of timber-concrete composite (TCC) floors is usually subjected to the requirement of serviceability based on design guideline standards rather than strength [3]. In order to control vibrations that occur in TCC structure, natural frequencies need to be sought first. This is because floor vibration is an up-and-down motion caused by forces applied directly to the floor as a result of human daily activity. Vibrations that occur in TCC floors are mainly caused by a floor length of more than 8 m. Thickness of concrete topping can also contribute to vibration issues in TCC floors. Floor vibrations generally make people feel uncomfortable to inhabit a building because it feels that it might collapse, especially if there is a cracking effect on walls and floors. Furthermore, the movement of washing machines is also capable of giving a slight impact to the structure of a building. The TCC laminated deck for structural systems has higher bending strength and lower deflection than a non-composite timber deck [4]. Reinforced concrete on top of timber also limits contact between water and timber elements. According to researchers [5], [6] and [7], other types of experiments and observations have been done on timber-concrete composites using different systems or designs.

The long-term behavior of Glues Wood-Concrete Composite floor was tested by [5]. Three scales of specimens were taken into account for the experimental investigations. The hygrothermal influence on the evolution of bond strength and time-dependent deformation was investigated with shear and bond specimens. These specimens were exposed 14 months to continuous loading and alternating climate in a climate chamber. Thus, numerical calculation methods were developed as a generalized prediction of long-term behavior on the structure. Natural seasonal changes of temperature and moisture content in wood can also influenced the deformation behavior of full-scale elements.

LVL-Concrete Composite floor was model by [6] using SAP 2000 software package. The finite element modeling was conducted on 2 m LVL - concrete composite (LCC) floors consisting of two parts between concrete floor and laminated veneer lumber (LVL) timber joist in order to study the vibration behavior of LCC with different concrete topping thickness. The natural frequency values produced through SAP2000 for the thickness of 25 mm and 65 mm are 57.45 Hz and 57.19 Hz, respectively. For thickness between 20 mm to 200 mm with a 20 mm interval, the optimum value found was achieved at 65 mm. For concrete topping less than 65 mm thick, the mass will influence floor behavior. Meanwhile, when concrete topping is more than 65 mm, floor behavior will be influenced by floor stiffness.

A series of Timber Concrete Composite (TCC) bridges were tested by [7]. This research was conducted for the possibilities of different types of shear connectors that can be offered by TCC structures for short-span bridge decks. Three types of shear connectors, namely screws, steel rebars glued to timber and steel mesh glued to timber were used. The first possibility is suitable for short-span rural bridges spanning up to 8 m. A low number of notches were used and high degree of composite action (nearly as in the case of fully rigid connection) was achieved. Another possibility for heavy loaded bridges is to connect glulam timber beams with a concrete slab using steel rebars and steel mesh. In addition, the concrete slab was to provide effective protection from the rain. All three TCC bridges described above represent effective possibilities to replace contemporary precast concrete and steel-concrete composite bridges in order to find a more pleasing solution sustainably and aesthetically.

This study aims to introduce a new laminated TCC system by using Malaysian Kempas timber. 20 nos of Kempas sawn timbers were laminated to produces the laminated deck which produce more strength to the floor. Then, the 3.6 m x 0.8 m TCC laminated deck system was constructed and experimented on using an electrodynamic shaker. An experimental modal analysis using SAP2000 was conducted on timber concrete composite samples with and without 0.065 m concrete topping in order to determine the vibration behavior.

2. TCC Laminated Deck

Malaysian Kempas timber was chosen as the timber joist for this study. This type of wood is considered as medium hardwood [8]. It has a density of 910 kg/m³ and an elastic modulus (G) of 12.5 Gpa. The dimensions for timber were 3600 mm (length) x 40 mm (width) x 90 mm (depth). However, Kempas timber cannot be used as only joist to construct TCC floors. It does not have the ability to withstand higher load, fire and water eruption. Thus, a bundle of Kempas timber was laminated by concrete to create a better performance joist and the TCC laminated deck was introduced. The concrete is also better in terms of fire performance because concrete on top of the deck can function as an efficient barrier against fire. Grade C35 concrete was used as the topping with a thickness of 0.065 m. The w/c ratio was 0.4 and the targeted slump ranged between 70-120 mm. Screws measuring 68.70 mm in length and 5.47 mm in diameter were used as shear connections. The spacing between the screws was 250 mm. Screws were added in order to prevent slip behavior.

Fig. 1 and Fig. 2 show the layout of TCC from a plan view and a side view. The TCC deck system was constructed using 20 pieces of Kempas sawn timber. Screws as connectors were placed on the surface of the timber with a spacing of 250 mm on the left and right side of the specimens. Meanwhile, a spacing of 500 mm between screws in the middle as shown in Fig. 3 was used. The bar size used for reinforcement was 12 mm. Furthermore, the reinforcement bars were tied together so that during concrete work, the structure of the laminated deck was not affected. In order to support the specimen, the I-beam was placed underneath. The beam was fixed by G-clamps which were placed at every edge to hold the specimen firmly in place during the test.

As shown in Table 1, two types of specimens were used in this study. The first specimen was timber concrete composite without topping (T1) and the second specimen was timber concrete composite with topping (T2). T1 specimens only contained timber without concrete on top. 20 pieces of Kempas timber were arranged side by side and connected using two rod bars. Meanwhile, T2 specimens had concrete topping on top of the timber.

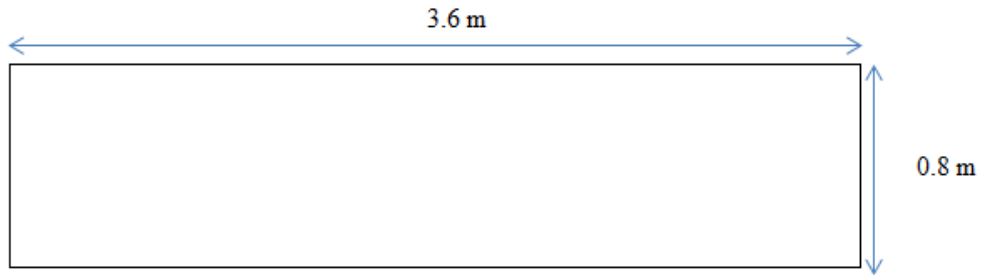


Fig. 1- Plan view for TCC deck

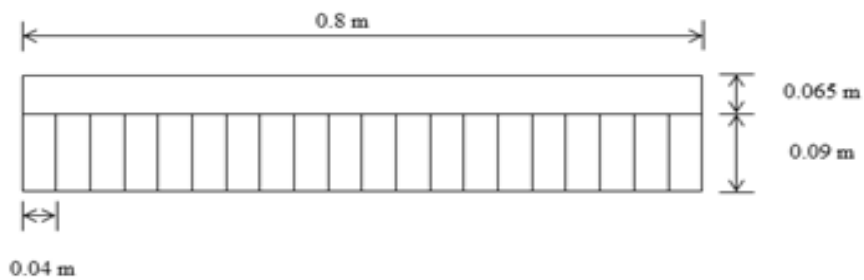


Fig. 2 - Side view for the TCC deck



Fig. 3 - Screws as the connector

Table 1 - TCC specimens

Type of Specimens	
<p>T1 (Timber only)</p>	

**T2
(TCC laminated deck)**



3. Modal Testing

Modal testing is a type of vibration test where the modal natural frequency, modal damping ratio and mode shape of a structure is determined. There are several ways to conduct modal testing which include shaker testing, impact hammer testing, walking testing and heel-drop testing. The type of testing stated can be done in order to determine natural frequency, damping ratio and mode shape.

For this research, the electrodynamic shaker (APS Electro-Seis) test was used to determine the vibration parameters. Once the structure is excited during the shaker test, the vibration response is measured. The data logger (imc CRONOflex) was used in order to record signals and compute the signals into frequency domain data. An accelerometer (KS48C with sensitivity 80 Hz) is an electronic sensor that converts electronic signals into accelerations. The accelerometer is a very sensitive piece of equipment that must be handled with care and needs to be placed on a flat surface to avoid noises that will occur from the bouncing floor. The data logger was connected to a laptop to read the test response.

3.1 Modal Testing Procedures

There are two types of tests conducted on the TCC deck specimens. T1 and T2 used the electrodynamic shaker as a vertical force. Twelve accelerometers were placed at different locations to obtain a better mode shape after analysis. The placement of accelerometers was the same for both surfaces. The frequency range for the shaker was set from 1 Hz to 100 Hz. The locations of the accelerometers were changed based on the total number of tests set for the shaker test. An electrodynamic shaker is a tool used to vibrate the specimen. This shaker was connected to the data logger and the data obtained was inserted into the IMC wave for analysis of the graphic form that occurs when the shaker vibrates. Meanwhile, Fig. 4 shows the numbered grid line and placement of shakers with reference points on the TCC laminated deck.

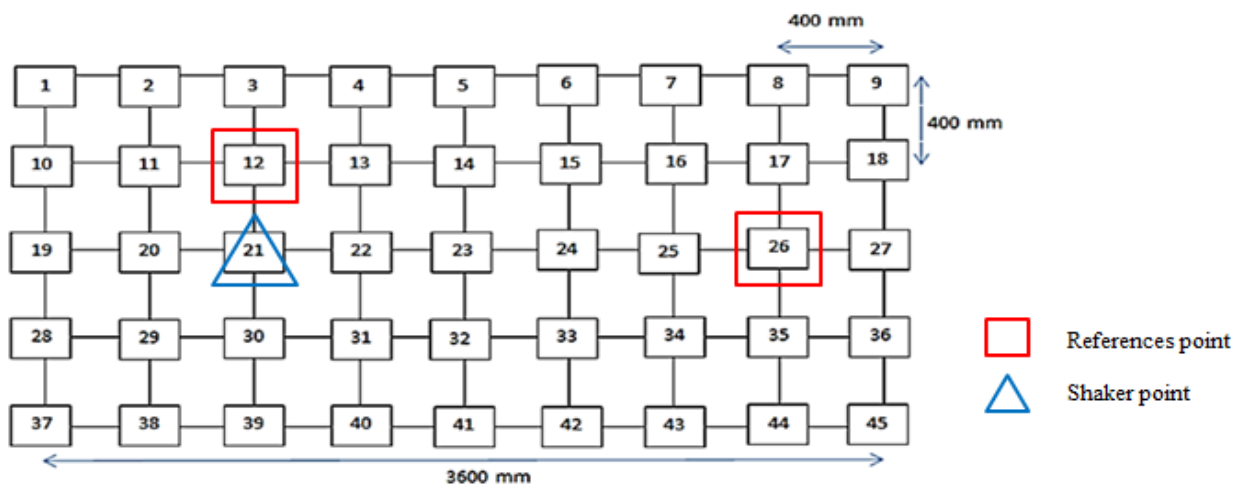


Fig. 4 - Numbered grid line

The key data acquisition parameters utilized in the FRF measurements are shown in Table 2. The measurement response in the time-domain was converted to FRF before the modal parameter of the floor was derived. The experimental modal parameter was determined by a curve fitting graph that was generated by the ME'scope [9] data processing software package.

The data was analyzed using ME'scope software and numerical methods. This software is intended to investigate changes that occur after vibration with a prescribed load imposed on TCC. It also post-processes the vibration data so that the data will be displayed visually. The frequency data from the data logger was imported to obtain the image of

vibration behavior that acted on the timber concrete component. Furthermore, the mode shape of the specimens was also acquired from the ME'scope software.

Table 2 - Data acquisition parameters adopted for FRF measurements

Parameter description	Parameter value
Sample rate	200 Hz
Data acquisition time	0.005 s
Total number of samples	1
Window	Exponential ($\lambda=0.001$)

The curve fitting method is a process used to obtain a set of modal parameters such as frequency, damping and mode shape for each of the modes of a structure that is represented in a set of Frequency Response Function (FRF) measurement data. As shown in Fig. 5 and Fig. 6 below, the graft before and after has been converted to an FFT graft. Me'scope contains three built-in curve fitting methods which are Quadrature peak, Peak Fit and MDOF Polynomial Fit. The MDOF Polynomial Fit has been proven to be one of the most reliable methods for estimating modal parameters. The MDOF can also be used to curve fit single reference or multiple reference FRF data sets. After the curve fitting, the peak picking method is done manually by choosing any suitable peak from the curve graft. The suitable peak must have a good natural frequency and damping value. 12.8 Hz is the first mode shape that was picked based on the peak picking method. After that, the mode shapes of 12.8 Hz are shown beside the graft in the software.

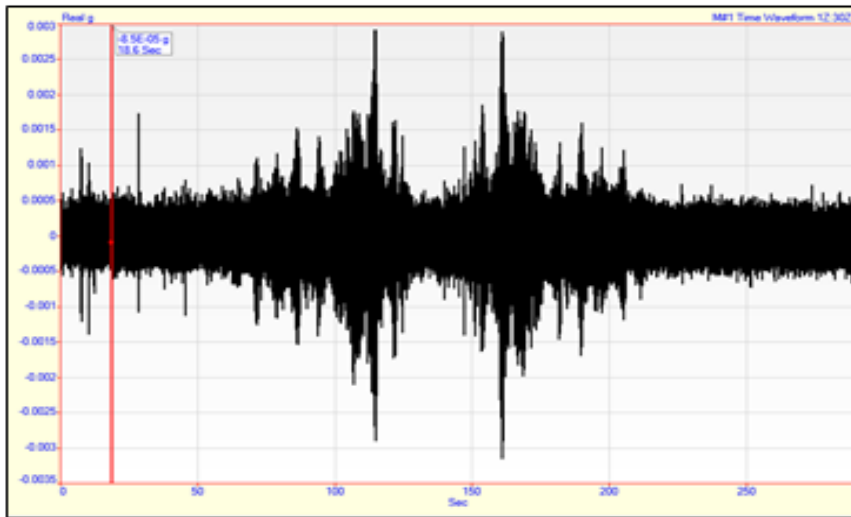


Fig. 5 - Frequency spectrum and curve-fit graph

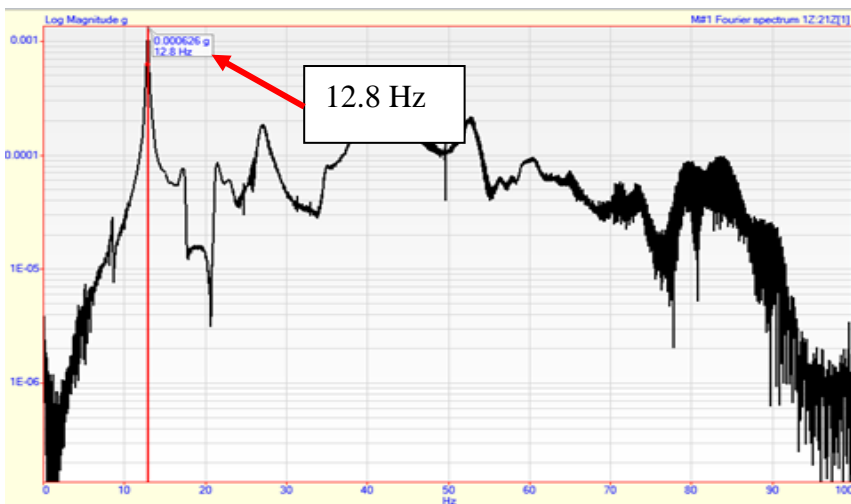


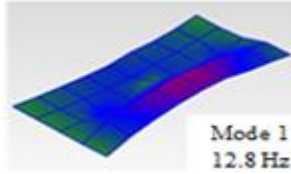
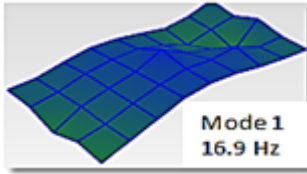
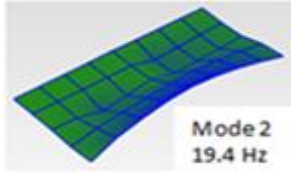
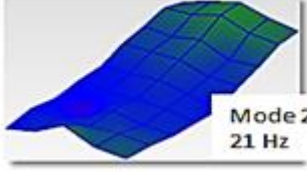
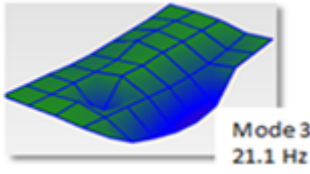
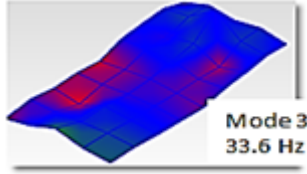
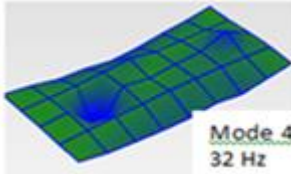
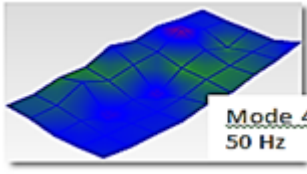
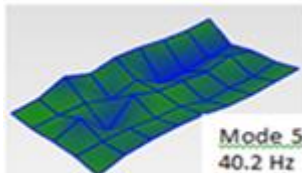
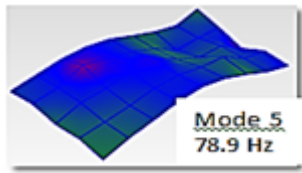
Fig. 6 - Modal peak function

4. Modal Testing Results

Table 4 below shows the mode shapes of T1 and T2 that were obtained from the experimental modal testing. The data was analyzed using the Me’scope package. The natural frequencies obtained from the experiment are 12.8 Hz for T1 and 16.9 Hz for T2, respectively.

The mode shapes obtained from the analysis should be correctly identified as the form represents the resulting vibration on the deck moving freely. Based on the analysis results, only the first three modes were considered in this study. According to [10], the mode shape is one of the important parameters for assessing vibration serviceability for structures. The mode shapes are represented as simpler sine waves with a specific pattern of vibration at a specific frequency. The shape for the first mode is half of a sine wave, the second mode is a full sine wave while the third mode shape is one and a half sine wave.

Table 3 - Mode shape from Me’scope Software

	T1	T2
Mode 1		
Mode 2		
Mode 3		
Mode 4		
Mode 5		

However, it is difficult to obtain a smooth mode shape due to the uneven surface of timber. In addition, there is probably a gap between timbers even after a rod bar has been installed. Table 3 displays the natural frequencies for T1 with a length of 3.6 m. The first mode shape for the timber floor has a frequency of 12.8 Hz. Meanwhile, the mode shape of T2 is much better than T1 as the surface of timber and concrete is interconnected properly using screws between the two composites. The first mode shape for T2 with a length of 3.6 m and a concrete topping of 0.065 m is 16.9 Hz, which is greater than 8 Hz or the limit for a timber concrete composite structure. Based on the modal analysis mode shape, it is considered acceptable due to the same range of frequency in the 1st mode which is greater than 8 Hz,

the limit set for TCC in Eurocode 5, Part 2, on timber bridges (CEN 2004a). The results of natural frequency of specimens with concrete topping and without concrete topping shows that the TCC deck structure has a high frequency of more than 8 Hz.

5. Finite Element Modeling

Table 4 and Table 5 below show the material properties of Kempas and concrete. The concrete was built based on the DOE method (British Standard) BS EN 1992-1-1:2004 Part 1-1.

Table 4 - Kempas properties

Material properties	Kempas
Unit weight (kg/m^3)	910
Elastic modulus, E (MPa)	12500000
Poisson's ratio, μ	0.369

Table 5 - Concrete material

Material properties	Concrete
Grade	C35
Unit weight (kg/m^3)	2354
Elastic modulus, E (MPa)	31000000
Shear modulus, G (N/mm^2)	956000
Poisson's ratio, μ	0.3

To model the slab, shell elements were used. Shell elements in SAP2000 are four-node elements with six degrees (U1, U2, U3, R1, R2 and R3) of freedom at each node. The thickness of a typical shell element is defined as the thickness of the slab itself. After the laminated deck and screw connections were created and connected through finite element modeling, the deck model was properly restrained so that the system acted appropriately. Finite element calculates frequency based on the mass and stiffness of the system independent of any loading on the slab structure. Fig. 7 shows the elevation view of the laminated deck. Screw links and rigid links were used to connect the concrete topping with Kempas timber.

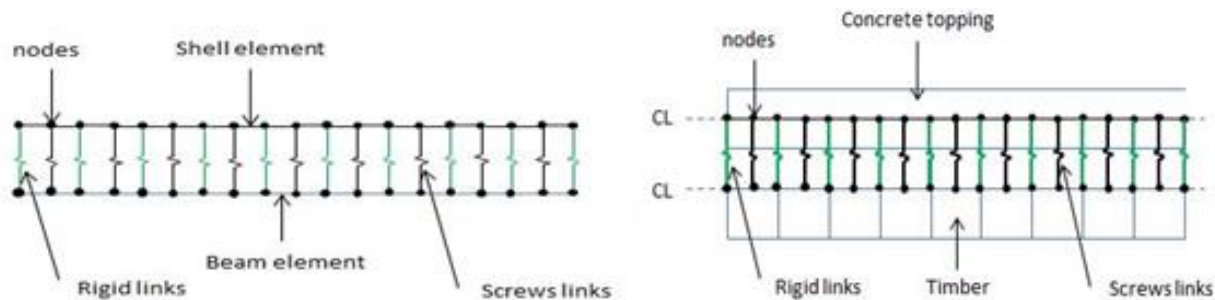


Fig 7 - Finite element modeling

Meanwhile, the results in Fig. 8 and Fig. 9 depict the natural frequency for both T1 and T2 TCC laminated decks from the model analysis which is deformed in the direction of x-axis for the three mode shapes. T1 shows the results in Fig. 7 with the first mode shape appearing at mode 1 with a frequency of 11.4 Hz. The second mode shape was deformed at mode 2 with a natural frequency of 22.6 Hz. The third mode shape was also deformed in the direction of the x-axis at mode 3 with a natural frequency of 34.9 Hz. Meanwhile, Fig. 8 shows the mode shape and natural frequency of T2 with a concrete topping of 0.065 m. The deformation behavior remained the same and occurred in the direction of the x-axis. The first mode shape deformed at 16.2 Hz, which is higher than T1. At mode 2, the deformation occurred at 32.3 Hz. The mode shape behavior for mode 3 also occurred in the direction of the x-axis with a natural frequency of 49.6 Hz. The increase in natural frequency in specimens with topping and without topping shows that the presence of concrete toppings makes a structure more stable. In addition, the proper connection between timber and concrete is also one of the reasons for the increase in natural frequency. The connection is sufficient to prevent shear force from developing between two materials. The mass provided by the concrete itself caused less vibration on TCC surfaces.

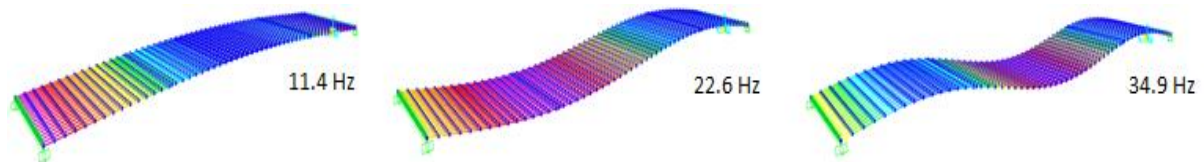


Fig. 8 - FE modal analysis on T1

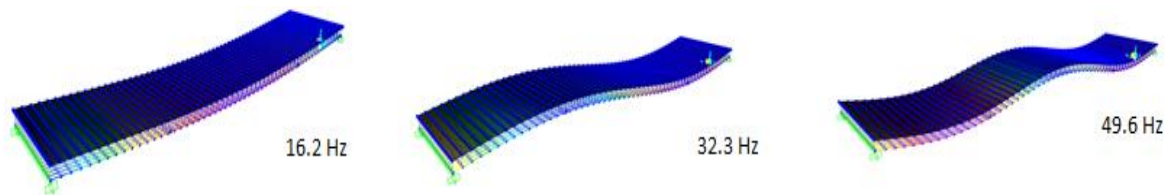


Fig. 9 - FE modal analysis on T2

6. Discussion

Based on Table 6 below, the experimental results are higher than the FE modeling results for T1 and T2 TCC decks. The experimental value is a result one obtains from the collected data in the form of a numerical value of the quantity of interest. Based on the differences obtained, the research results are not affected because according to [11] research; there is a comparison of the first bending mode obtained from the experiment and FE modeling where the highest difference is 18.5%. The highest differences for the T1 deck and the T2 deck are 10.9 % and 4.1 %, respectively. Therefore, the percentage difference is acceptable.

Besides that, all the frequencies from both analyses for T1 and T2 show that the frequencies were far greater than 8 Hz [12]. The frequencies are greater than 8 Hz because the stiffness of the TCC laminated deck was increase due to the timber pieces were connected using rod bars in order to gain more strength and durability. With the addition of concrete topping and screws as shear connectors, the deck can withstand higher load. The length of specimens can also provide high frequency and increase deck stiffness. [13] stated that the natural frequency of floors should be at least 8 Hz or greater because if the frequency is below 8 Hz (Eurocode 5, Part 2 - clause 7.3.3-1), humans can easily feel the vibration. Usually a problem arises when the forcing frequency value is close enough to the natural frequency obtained from the analysis. Therefore, the design of the floor should have a higher natural frequency value compared to the forcing frequency of 8 Hz.

Table 6 - Comparison of natural frequency between experimental testing and FEM

Deck	Experimental [Hz] (Me'scope)	FE [Hz] (SAP2000)	Percentage differences (%)
T1	12.8	11.4	10.9
T2	16.9	16.2	4.1

7. Conclusion

The study shows that TCC laminated decks T1 and T2 can provide comfort and safety for occupants to feel safe in a building. Through the results obtained from the Me'scope analysis, the frequency obtained is almost similar to that obtained from FE modeling. The natural frequency of first mode shape for T1 and T2 is also greater than 8 Hz. According to [8] (clause 7.3.3-1), all residential floors need to achieve a fundamental frequency of more than 8 Hz. Based on the results of natural frequency from the ME'scope software, T1 has a high frequency of more than 8 Hz. Meanwhile, the FE modal analysis also shows that the natural frequency for the first three mode shapes is more than 8 Hz. The first mode shape generates a frequency of 16.2 Hz in the direction of the x-axis. The other two mode shapes are also in the direction of the x-axis with frequencies of 32.3 Hz and 49.6 Hz, respectively.

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