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Research article

Numerical study of pedestrian suspension bridge with innovative composite deck

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ABSTRACT

The increasing trend of using light and slender deck in pedestrian bridge has raised the issue of instability under pedestrian movement. The suspension pedestrian bridges are more vulnerable as lateral vibration often occurred in such type of bridges. Hence, the current paper targeted to develop a pedestrian suspension bridge with a new type of composite deck using Glass Fibre Reinforced Polymer (GFRP) in the bottom layer and laminated glass in the top layer. The safety and serviceability of the developed pedestrian bridge is rigorously investigated. The performance of the suspension pedestrian bridge is comprehensively investigated by monitoring important response parameters such as stress, deflections, natural frequencies and accelerations under pedestrian loads and compared with current bridge design code requirements. The developed suspension pedestrian bridge with new type of composite deck could adhere the requirements of the bridge design code. Hence, the suspension pedestrian bridge mentioned in this paper is recommended for pedestrian use for its standard safety and serviceability.

1. Introduction

Natural frequency usually founds to be low for a slender suspension pedestrian bridge. Such type of bridge often susceptible to dynamic loads due to the movement of multiple pedestrians. Past reports inform that considerable lateral vibration was found in few of the constructed suspension pedestrian bridges under movement of large volume of pedestrian [1].

Several research studies investigated the reason of occurring excessive lateral vibration and determine the lateral vibration of suspension pedestrian bridges [2,3,4,5,6,7]. Most of the researchers identified the lateral component of load of moving pedestrians as the main reason of occurring the lateral vibration [7]. Excessive lateral vibration can lead to instability issues among the pedestrian or even can be the cause of potential accidents [8]. Jun and Qin [9] has summarized the instability incidents of suspension pedestrian bridge.

On the contrary, slender suspension pedestrian bridges composed of light deck materials are becoming popular in the recent years. In a consequence, a few types of new and light materials are introduced to be used in the deck of pedestrian bridges by several researchers. For instances, Dey et al. [10], developed an aluminum deck pedestrian bridge and investigated the dynamic performance of the particular pedestrian bridge. Junpeng et al. [11], explored the performance of a steel box girder self-anchored pedestrian suspension bridge through measuring natural frequency.

In the recent times, fibre polymers as being light-weight materials is becoming popular in manufacturing light deck for pedestrian bridges. Fibre reinforced polymer (FRP) was selected by researchers due to its few utilizing benefits such as high strength to weight ratio, ease in installment, durable, available in different sizes and colours etc. Votsis et al. [12], investigated the dynamic response of suspension bridge composed of FRP deck and predicted the vulnerability of the bridge due to lateral vibration developed by dense pedestrians. Researchers also aimed to increase the strength and stiffness of FRP material was by adding carbon fibre or glass fibre into the fibre composite material. However, glass fibre reinforced polymer (GFRP) was preferred compared to carbon fibre reinforced polymer (CFRP) due to economic reason. Wei et al. [13], explored the behaviour of suspension pedestrian bridge where the bridge deck was made up of GFRP. Nevertheless, Wei et al. [13], noticed that the natural frequency of the proposed pedestrian bridge was low and fall within the natural frequencies of human pacing rate. Recently, Sa et al. [14], proposed a GFRP-Steel composite pedestrian bridge where the steel

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beams were in full connection with the GFRP bridge deck and supported the GFRP bridge deck. Sa et al. [14], found the maximum accelerations developed due to fast movement of pedestrians and crowd movement over the pedestrian bridge higher than the recommended values of Bridge Design Codes. Under such situation, Sa et al. [14], hence restricted the use of the composite pedestrian bridge only for normal walking pedestrians.

There have been some other measures investigated by the researchers to enhance the dynamic response of suspension pedestrian bridge built up with light deck materials and to prevent resonance. For example, Paul and Brian [15] suggested GFRP beam with GFRP lateral bracing to support a timber deck. Faridani and Barghian [16] improved suspension bridge hanger system by adding horizontal cable between two adjacent hangers and thereby enhance the dynamic performance of the bridge. The use of TMD is also well accepted by the researchers and engineers as it can increase damping of the pedestrian suspension bridge and control the vibration and acceleration developed due to crowd movement [1, 17, 18]. Platform test (Figure 1(b)) using the deck material is usually carried out to determine the location of the TMDs. The effectiveness of introducing TMDs for a typical pedestrian suspension bridge to avoid resonance was elaborately explained by Nimmen et al. [17]. In addition, the use of high damping rubber strips accompanied with TMD was also found effective in reducing vibration and consequently avoiding resonance by Asta et al. [18].

However, the modification of the parts of suspension pedestrian bridges or retrofitting them after design and installation can be costly and or cumbersome. Under these circumstances, improving the dynamic performance of suspension pedestrian bridges by introducing innovative composite bridge decks made up of high strength, stiff, durable and cost effective materials, can be a feasible option. There is hence the necessity for further research to find new and effective compositions of suspension bridge decks to meet the modern design trends, enable use under all types of pedestrian movements and curb the vibration and acceleration to be within the suggested values of Bridge Design Codes (BS 5400, ENV 1995-2, Ontario Bridge Design Codes).

To address the above mentioned issues, the present study proposes a bi-layer composite deck for pedestrian suspension bridge by using laminated GFRP plate in the bottom layer and laminated glass in the top layer of the deck of the proposed pedestrian suspension bridge. The overall performance of the pedestrian suspension bridge with the proposed composite deck is analyzed in ABAQUS Finite Element software. The vital response parameters such as stress, deflection, natural frequency and acceleration are verified with the suggested numbers of Bridge Design Codes. The safety and serviceability of the developed suspension pedestrian bridge is carefully considered in the present study.

In short, the present paper attempted to propose a bi-layer composite deck where the bottom layer is made up of light material and the top layer with stiff material in order to eliminate the retrofitting and at the same time ensure a safe and serviceable pedestrian bridge. So, the bridge deck will be heavier than the previously proposed light deck but the retrofitting will not be required.

2. Validation of modelling techniques of suspension bridge

Results of experimental free vibration testing [19] and numerical modelling [20] of the Olfusá suspension bridge, available in the literature are used to validate the modelling techniques used in this paper. In this purpose, a three-dimensional Finite Element (FE) model of Olfusá suspension bridge was established in ABAQUS to determine its dynamic response parameters.

2.1. Introduction of Olfusá bridge

The suspension bridge over Olfusá river consists of a 84m single span with a maximum cable sag of 10.5 m and tower/pylon height of 10.2 m. The bridge pylons are made up of two steel I beams riveted together by a steel plate and filled with concrete. The base of the pylon is hinged to allow rotation in the transverse direction of the bridge. The deck of the suspension bridge is composed of concrete and the total width and thickness of the deck of the suspension bridge is 8.7 m and 150 mm respectively. The suspension system has a total 12 cables, with 6 cables in each longitudinal sides of the bridge deck. Each cable is a locked coil strand and composed of 96 wires. The diameter of each cable is 60.1 mm, providing an active steel cross-sectional area of 2174 mm^2 [19, 20]. The cables are anchored on either side in a large concrete block. Figure 1 illustrates the longitudinal profile of Olfusá suspension bridge.

The bridge deck is suspended from the cables by hangers in the form of circular solid steel bars. There are 20 hangers on either side of the cable at 4 m intervals and the diameter of each cable is 50.8 mm. The length of each hanger on both sides of cable is mentioned in Pálsson [19] and Wickramasinghe et al., [20]. The bridge is stiffened by using several longitudinal I beams, longitudinal trusses, transverse trusses, wind bracings and diagonal bracings. Four longitudinal upper I beams are used to support the concrete deck of the suspension bridge. The I beams are carried by the transverse trusses of the suspension bridge. Again, two longitudinal lower I beams are introduced to support the transverse trusses. Longitudinal truss is also used above each of the lower I beam to support the deck of the suspension bridge. Two vertical longitudinal trusses and 22 transverse trusses are utilized and the depth of the longitudinal and transverse trusses are 1.687 m and 1.496 m respectively. The parts of the suspension bridge are shown in Figure 2. The geometric and material properties provided by Wickramasinghe et al. [20], and Pálsson [19], respectively are given from Tables 1, 2, 3, 4. The Young's modulus was found lower than the Young's modulus of steel as paint was fallen in some of the locations of the mentioned parts of this old bridge and corrosion occurred which reduced strength Pálsson [19].

2.2. FE model development of Olfusá bridge and analysis

Three-dimensional FE model of Olfusá bridge was established in ABAQUS to determine the natural frequencies and mode shapes of the suspension bridge. The developed FE model representing the bridge deck, suspended cables, hangers, pylon, and stiffening girders. The parts of the stiffening girder as mentioned in Figure 2 were used to prepare the

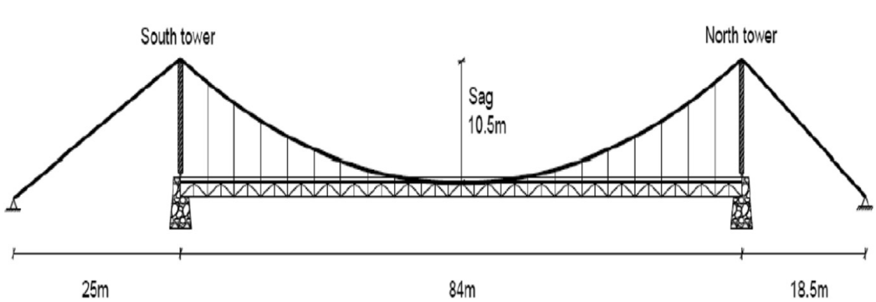


Figure 1. Longitudinal profile of Olfusá bridge [19, 20]

(a) (b)

Figure 2. View of Olfusá suspension bridge (a) longitudinal & transverse trusses (b) cable arrangement [19, 20].

Table 1. Geometric properties of longitudinal I girders sections.

Section Type	Area (mm^2)	I_{xx} (mm^4)	I_{yy} (mm^4)
Inner top chord (upper)	8514	1.8E+08	8.7E+06
Outer top chord (end)	7996	1.6E+08	1.5E+07
Outer top chord (mid)	12743	1.9E+06	1.1E+07
Bottom chord (end)	13068	2.6E+08	2.5E+07
Outer top chord (mid)	16708	2.9E+08	2.6E+07

Table 2. Geometric properties of longitudinal truss sections.

Section Type	Area (mm^2)	I_{xx} (mm^4)	I_{yy} (mm^4)
Diagonals (0–4 m)	5956	5.6E+06	1.4E+08
Diagonals (4–8 m)	4838	4.6E+06	1.1E+07
Diagonals (rest of span)	3680	3.6E+06	8.2E+06
Vertical angles (2, 6, 10 m…)	1357	7.3E+05	7.3E+05
Vertical angles (4, 8, 12 m…)	2660	2.1E+06	2.2E+06
Wind bracing	2060	2.6E+06	2.6E+06

Table 3. Geometric properties of transverse truss sections.

Section Type	Area (mm^2)	I_{xx} (mm^4)	I_{yy} (mm^4)
Horizontal top angle	4247	4.1E+06	9.4E+06
Horizontal bottom angle	8247	7.3E+06	2.2E+07
Diagonals (inner)	2660	2.1E+06	2.2E+06
Cross bracing (middle)	1345	1.1E+06	4.5E+05
Diagonals (outer)	3170	2.4E+06	5.6E+06
Vertical angles	2660	2.1E+06	2.2E+06

FE model. The suspended cables, hangers, and stiffening girders were composed of 2-node linear beam elements (B31). The steel and concrete segments of the pylon was made up of 8-node linear brick elements with reduced integration and hourglass control (C3D8R). The bridge deck of the particular suspension bridge was composed of 8-node quadrilateral shell element with reduced integration and hourglass control (SC8R). Circular section was defined for cables and hangers and angles were defined for stiffening girders. The geometric sections and cross-sectional

Table 4. Mechanical properties of structural parts of Olfusá bridge.

Material	Density (kg/m^3)	Young's Modulus, E (GPa)	Poisson's ratio, υ
Steel of cables (considering corrosion and deterioration)	8000	135	0.3
Steel of hangers (considering corrosion and deterioration)	8000	135	0.3
Steel of pylon	8000	210	0.3
Concrete of pylon	2500	32	0.2
Concrete of bridge deck	2500	32	0.2
Steel of truss & stiffening girder (taking consideration of connections and rivets)	9000	210	0.3

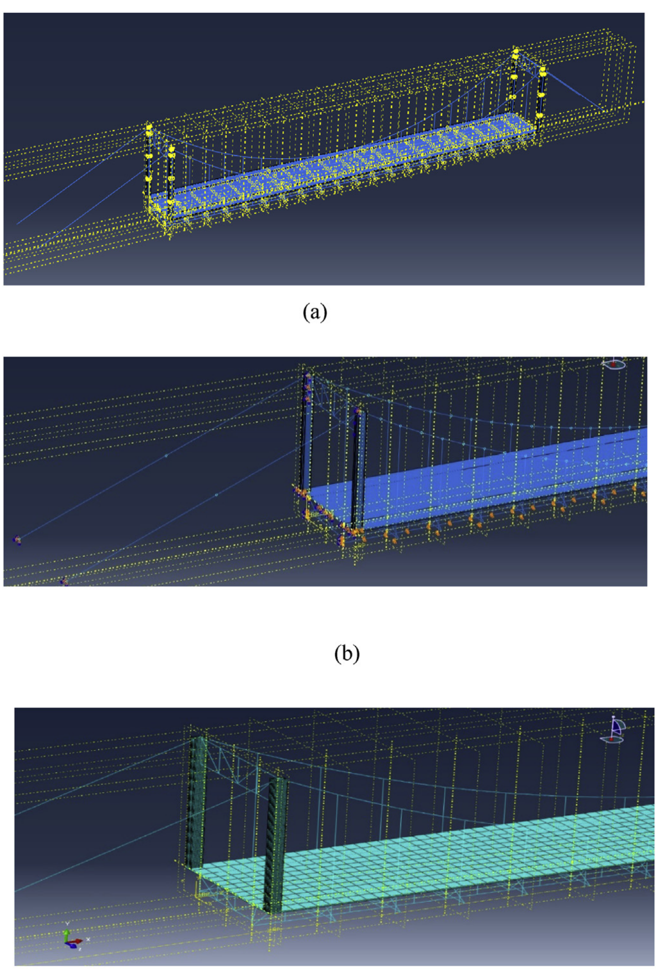
mentioned by Wickramasinghe et al. [20], were used to prepare the structural parts of FE model. The geometric properties and the material properties of various members of the suspension bridge are presented in Tables 1, 2, 3, 4.

The mesh size applied for bridge deck and pylon in the FE model of the suspension bridge was 750 mm and 100 mm, respectively. Single element for each segment was selected for the members of the suspension bridge which were composed of beam elements. The contact surfaces of the adjacent members of the suspension bridge were defined by tied constraints.

Pinned support conditions were defined at the bottoms of all hangers whereas vertical (UR2) and lateral (UR3) rotation restrained conditions were defined at the tops of all hangers to simulate the real condition. Other edges and ends of the parts of the suspension bridge as shown in Figure 3 (b) were provided fixed boundary conditions. Figure 3 shows the established FE model of the Olfusá suspension bridge.

2.3. FE model validation of Olfusá suspension bridge

First mode and second mode natural frequencies were determined from the established FE model of Olfusá suspension bridge. The noted frequencies were compared with the corresponding natural frequencies measured by Pálsson [19] and the numerical values of these frequencies obtained from Wickramasinghe et al., [20]. The results are shown in Table 5 which informs that the present results obtained from the developed FE model compared well with previous experimental and numerical results and provides reliability in the modelling strategies utilized in the previous sub-sections.



(a)

(b)

(c)

Figure 3. FE modelling of Olfusá suspension bridge (a) FE model (b) Boundary condition of FE model (c) FE meshing.

Moreover, the mode shapes for first and second order natural frequencies (Figure 4) determined from the developed FE model were also found to be similar (vertical and lateral dominant respectively) to those noted by Pálsson [19]. Hence, the modelling techniques applied for the established FE model of the suspension bridge can be considered as reliable to determine the performance of a suspension bridge.

3. Design methodology of composite suspension bridge

The procedure of design of an innovative composite pedestrian suspension bridge adopted in this study is comprised of several steps. First of all, the materials and composition of deck of pedestrian bridge are selected to satisfy the recent design trends and also considering the effectiveness of the materials. An innovative bi-layer composite deck following flexible-stiff combination is considered for the present study. Such combination is adopted to add some rigidity in certain portion of bridge deck and hence to reduce the probability of vibration of light pedestrian suspension bridge. The innovative composite deck was consisted of Glass Fibre Reinforced Polymer (GFRP) at its bottom layer and laminated glass at its top layer. The verification of the proposed composite deck was conducted in ABAQUS using the test results of static compressive test on similar composite deck. The tentative dimensions and standard mechanical properties of the various members of the proposed suspension pedestrian bridge were selected to understand the static and dynamic performance of the proposed bridge. Furthermore, the effectiveness of the innovative slender pedestrian suspension bridge is further evaluated in this study by monitoring the safety and serviceability level of the bridge under fast movement of dense pedestrians. Furthermore, the significance dimensions of other members of the proposed suspension pedestrian bridge on the static and dynamic response of the composite bridge is also explored in the study. For this purpose, an advanced three-dimensional FE model almost similar to the validated FE model of suspension bridge described in the previous section is developed in ABAQUS to observe the static and dynamic responses of the proposed composite pedestrian suspension bridge. The systematic design procedure through FE analysis requires several trials to satisfy the safety and serviceability requirements set by Bridge Design Code. Thereafter, design guidelines are developed for that particular suspension pedestrian bridge.

The methodology designed to predict the performance of the proposed suspension pedestrian bridge is presented in Figure 5.

3.1. Introduction and model validation of proposed composite deck

3.1.1. Description of proposed innovative deck

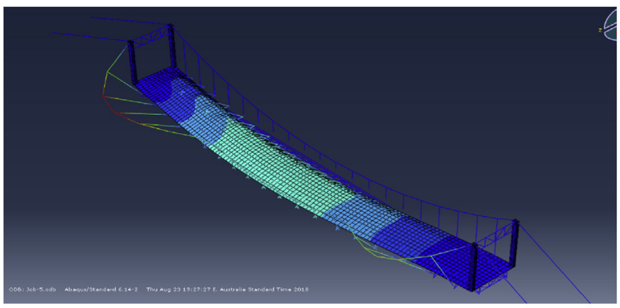
In recent years, the use of GFRP material is increasing due to its high value of tensile strength, light weight, availability in a variety of colors and ease in installation. So, GFRP material is selected for the bottom layer of the bi-layer composite bridge deck. Laminated glass is selected for the top layer of the innovative deck due to its durability, transparency and stiffness. The combination of these two materials in different layers of bridge deck is expected to increase the dynamic performance of the composite pedestrian suspension bridge due to enhanced stiffness of a part of the bridge deck. In doing so, the composite pedestrian suspension bridge is expected to be effective to control excessive vibration and acceleration of the overall structure, which are the main issues of using light deck materials. The composition of the innovative deck considered in the design of the proposed bridge is shown in Figure 6.

3.1.2. Static compressive test on proposed innovative deck

Experimental investigation through static compressive test was conducted on the proposed deck as mentioned in Figure 6. The bi-layer composite deck was 1000 mm by 400 mm and 16.5 mm in overall thickness. The individual layer thicknesses of the laminated GFRP plate

Table 5. Comparison of natural frequencies.

Natural Frequency (Hz)	FE analysis results	Measurement by Pálsson (2012) [19] (I)	Numerical results of Wickramasinghe et al. (2016) [20] (II)	Deviation (%) from I	Deviation (%) from II
First mode	1.09	1.08	1.07	0.92	1.83
Second mode	1.66	1.61	1.60	3.01	3.13



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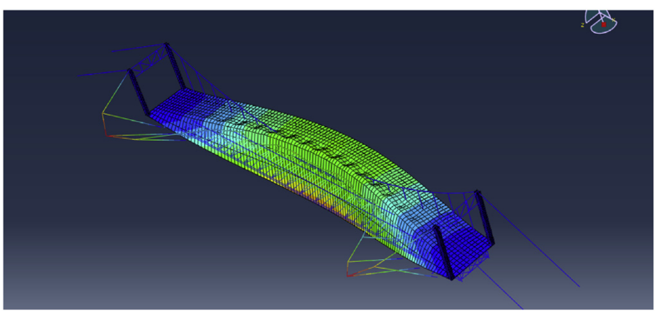


(b)

Figure 4. Natural frequencies and modes of vibration (a) first mode (b) second mode.

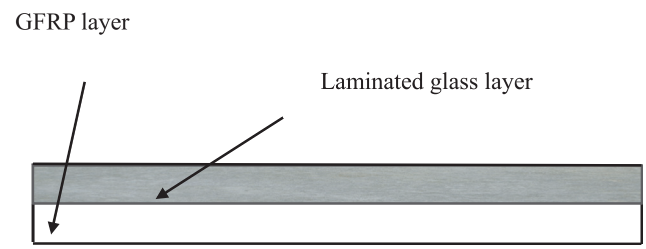


Figure 6. Illustration of bi-layer composite deck.

and laminated glass were 10 mm and 6.5 mm, respectively. The top and bottom layer of deck was attached by using high strength adhesive. The mechanical properties of the materials used in the composite plate are mentioned in Table 6.

Figure 7 shows the test set up adopted for static compression test on the innovative composite deck. The bi-layer composite specimen was fastened at around 50 mm from the end by using 10 mm circular aluminum rod. The center of the top of the composite plate was loaded with metal cylinder with total weight of 5 kg. Two LVDTs were attached over the GFRP layer of the specimen by using a wooden frame. Deflections in the vertical directions were measured under the application of load. The locations of the LVDTs are shown in Figure 7(b).

3.1.3. Preparation of FE model and verification

A three-dimensional FE model of the innovative bi-layer composite deck as described in previous sub-section was established in ABAQUS and validated by using the test data of the static compressive test. The developed FE model of the deck was composed of laminated GFRP and

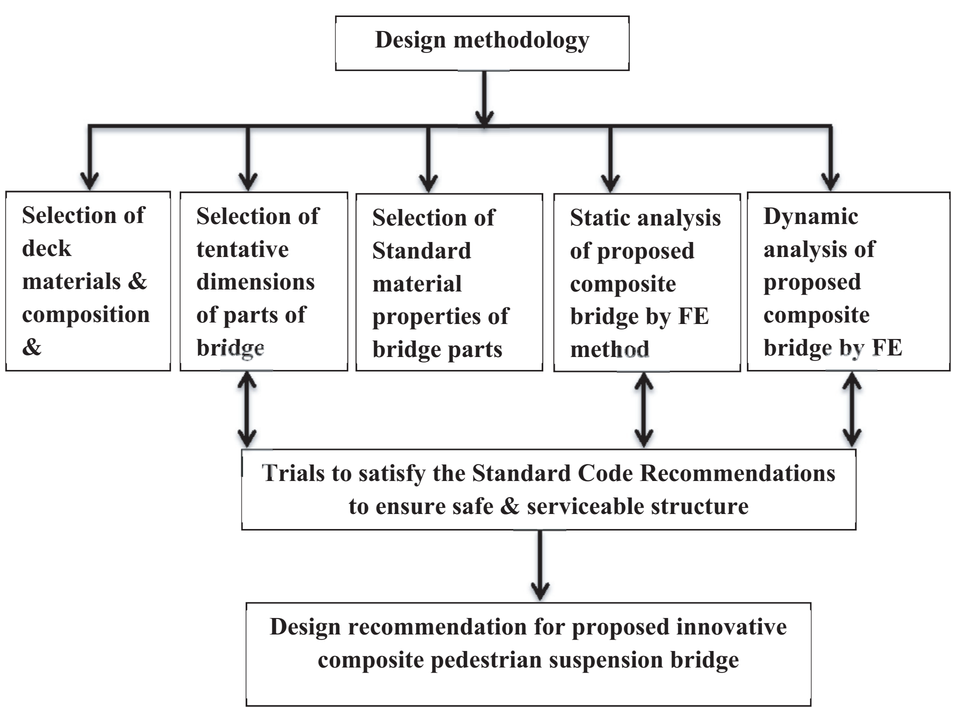
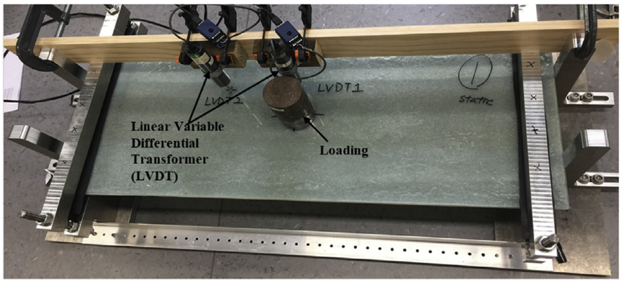


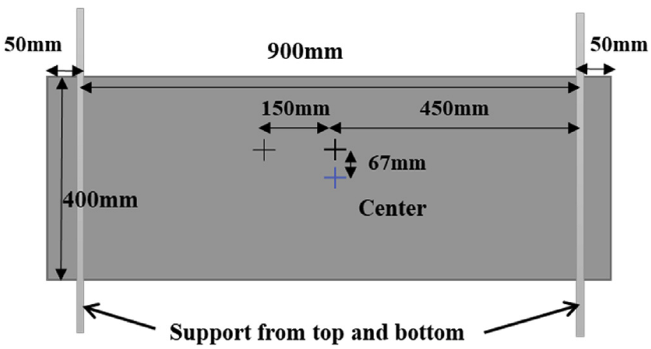
Figure 5. Design methodology for composite pedestrian suspension bridge.

Table 6. Material properties of materials of composite deck.

Material	Thickness (mm)	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
GFRP	10	1250	1.40	0.30
Laminated glass	6.5	2000	22	0.22



(a)



(b)

Figure 7. Test set up of static compressive test of composite plate (a) test set up (b) location of LVDTs.

laminated glass at the top and bottom layer of the deck, respectively (Figure 8).

Individual layers of the FE model of the bridge deck were defined as solid bodies and three-dimensional linear brick elements were used to compose the layers of the bridge deck. Mechanical properties provided in Table 6 were selected for the FE model of bridge deck. GFRP Tied constraint was considered to define the full connection at the contact surface of the bridge deck.

A circular area of 73 mm diameter was considered at the top center of laminated glass layer to simulate the test condition and to apply load. An equivalent load of 5 kg was applied over the circular area as surface pressure of 11670 Pa. The top and bottom layer of the bridge were provided pin constraint at 50 mm from the edge resembling the test conditions. Mesh size of 10 mm was considered for both layer of the bridge deck.

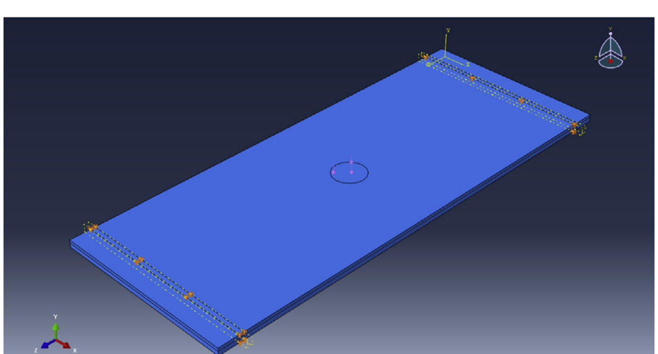


Figure 8. FE model of the innovative deck.

Table 7 presents the deflections noted from the static compressive test and the FE analysis of the bridge deck.

Table 7 shows the test results for different LVDTs for two identical bridge deck specimens and compares the test results with the results obtained from the developed FE model. Table 7 shows that a deviation of 6.06% and 3.00% was found for sample 1 and 2, respectively from test results for LVDT 1 whereas the deviation was 8.00% and 0% for sample 1 and 2, respectively from test results for LVDT 2. In addition, the small COV values also indicated that the FE results matches well with the test results. Therefore, the established FE model of the innovative deck is expected to predict the response of proposed composite deck accurately.

3.2. Proposed suspension pedestrian bridge

The proposed suspension pedestrian bridge is consists of a single span and the span and total width of the bridge is 25m and 3 m, respectively. The architectural pattern of the proposed suspension bridge is almost similar to that of the Olfusá suspension bridge (shown in Figure 1) which was selected for validation purpose in the previous section. However, the cable anchoring is considered symmetric for the suspension pedestrian bridge and it is assumed that the horizontal distance of the cable anchoring location from the bridge tower is 4 m. The tentative dimensions for the proposed pedestrian bridge is selected by maintaining compatibility with span length ratio of the proposed pedestrian suspension bridge and the Olfusá suspension bridge. Innovative bi-layer composite deck using GFRP-laminated glass is adopted as the deck of proposed suspension pedestrian bridge which is shown in Figure 6. The preliminary thicknesses of the laminated GFRP layer and laminated glass layer are adopted equal and several trials are carried out to find the effective thickness.

A single cable is considered at each sides of the pedestrian suspension bridge with a diameter of 60 mm. The hangers are considered to be composed of circular solid steel bars with diameter of 20 mm. In total, 9 hangers are attached to each of the two cables at horizontal spacing of 2.5 m. The heights of the bridge tower above the top of the deck and below the top of the deck are selected as 3 m and 2.5 m respectively. The dimension of the tower is adopted as 300 mm × 300 mm and the tower is considered to be made up of concrete. The cable sag of the proposed suspension pedestrian bridge is 2.5 m and hence a sag ratio of around 0.1 is considered. The bridge deck is stiffened by using two longitudinal beams with HEB 750 profile and nine transverse beams with HEM 280 profile. The longitudinal beams are supported by the bottom part of the tower of this suspension bridge. Standard properties of materials selected for this composite suspension bridge are shown in Table 8. The elastic modulus of concrete is 32 GPa and hence the concrete is expected to be of normal strength.

3.3. FE model development and analysis

3.3.1. Static design

Three dimensional FE model of proposed suspension pedestrian bridge (Figure 9) is established in ABAQUS following the similar modelling strategy as considered for the validated FE model of Olfusá bridge. The FE model of proposed pedestrian suspension bridge is composed of innovative composite bridge deck, tension cables, hangers, towers, longitudinal girders and transverse girders. The FE model of

Table 7. Test and FE results of the innovative deck.

Type of LVDT	Deflection (mm)			FE & Sample 1		FE & Sample 2	
	Experimental		FE analysis	Deviation (%)	COV	Deviation (%)	COV
	Sample 1	Sample 2					
L1	0.31	0.32	0.33	6.06	0.044	3.00	0.043
L2	0.23	0.25	0.25	8.00	0.058	0	0

Table 8. Material properties of proposed composite pedestrian suspension bridge.

Material	Density (kg/m^3)	Young's Modulus, E (GPa)	Poisson's ratio, υ
Steel of cables	8000	135	0.3
Steel of hangers	8000	135	0.3
Steel of pylon	8000	210	0.3
Concrete of pylon	2500	32	0.2
Concrete of bridge deck	2500	32	0.2
Steel of truss	9000	210	0.3

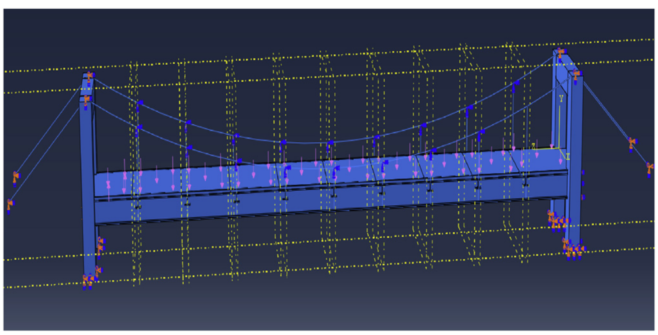


Figure 9. FE model of proposed suspension bridge under static loads.

laminated GFRP-laminated glass deck is defined analogously as mention in section 3.1.3.

The mechanical properties (Table 9) of laminated GFRP plate and laminated glass is collected from Ou et al. [21], and Froling [22] which are used for the FE analysis of the proposed suspension pedestrian bridge. Laminated GFRP plate is defined as a set of layers and the modelling details ae mentioned in Ali et al., [23]. The modelling strategies adopted for laminated glad are described in Ali et al., [24]. Short glass fibers with area of around 0.473 mm^2 were used in epoxy resin matrix to get the properties mentioned in Table 9. The paper mentioned the fiber volume fraction as 35% of total volume of laminated GFRP plate.

Material properties of Table 6 were used only for FE model validation purpose instead of evaluating the static and dynamic response of suspension pedestrian bridge with proposed innovative deck. This is because the required strength properties of laminated GFRP plate and laminated glass were not found which were purchased for lab testing purpose. The required strength implies that it was not sufficient for ensuring safety and serviceability for the proposed suspension pedestrian bridge from FE analysis. Hence, authors used the properties (Table 9) of high strength laminated GFRP plate and laminated glass from literature.

The values of Table 9 were used to prepare the composite deck in the FE analysis of proposed suspension pedestrian bridge and evaluate the performance of large scale pedestrian suspension bridge by FE analysis.

The suspended cables and hangers are modelled using 2-node linear beam elements (B31) and circular section profiles are considered for these members of the proposed suspension pedestrian bridge.

The longitudinal and transverse steel beams and concrete tower are defined by 8-node linear brick elements with reduced integration and hourglass control (C3D8R). Table 8 presents the mechanical properties of the members of the proposed suspension pedestrian bridge. The tentative geometric properties of different members used for the developed FE model of suspension pedestrian bridge are presented in Table 10.

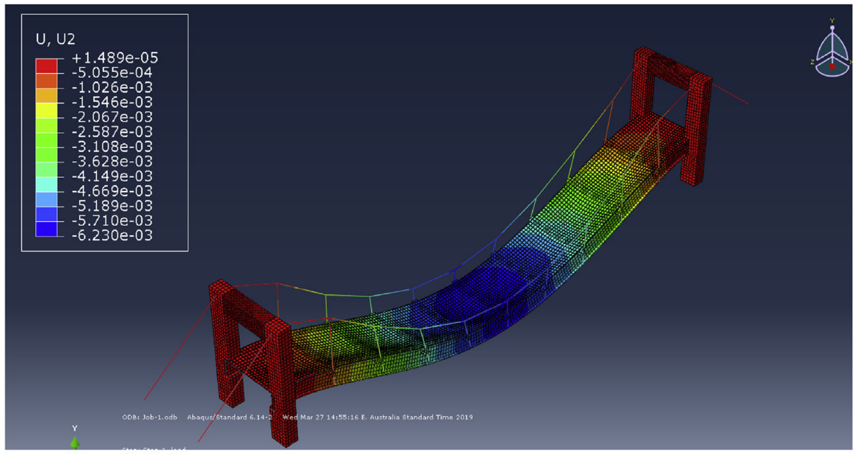
Mesh convergence studies were carried out to select the mesh sizes of different parts of the proposed bridge model. Mesh sizes for layer of laminated GFRP plate and laminated glass of the proposed bridge deck of the suspension pedestrian bridge are selected as 100 mm. For

Table 9. Mechanical properties of materials of proposed bridge deck.

Material	Ply thickness (mm)	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Tensile strength (MPa)	No. of ply layers
GFRP	0.50	1800	14.10	0.30	_	550	20
Laminated glass	_	2500	72.00	0.22	100	_	_

Table 10. Geometric properties of different members of proposed suspension pedestrian bridge.

Parts	Cross-section Type	Dimension
GFRP layer of deck (Tentative)	Rectangular	3000 mm × 10 mm
Laminated glass layer of deck (Tentative)	Rectangular	3000 mm × 10 mm
Hanger	Circular	Diameter: 20 mm
Cable	Cable	Diameter: 50 mm
Tower	Square	300 mm × 300 mm
Longitudinal beam	H-section	Width = 300 mm, height = 750 mm, thickness = 32 mm
Transverse beam	H-section	Width = 288 mm, height = 310 mm, thickness = 18.5 mm



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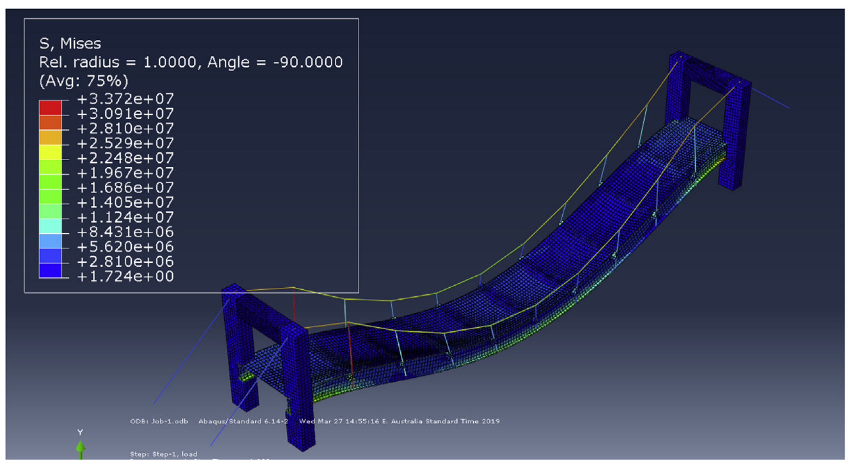


(b)

Figure 10. Static response of proposed suspension pedestrian bridge (a) deflection contours (b) stress contours.

longitudinal beams, transverse beams and concrete tower, the mesh sizes are considered as 150 mm. The cable and hanger parts of the proposed suspension pedestrian bridge are meshed by defining a single element between two neighbouring joints. The contact surfaces of laminated GFRP plate and laminated glass layers are defined by tied constraint. Similarly, the contact surfaces of longitudinal beams and bridge deck, and also the common surfaces of transverse beams and composite deck are tied by using the tie constraint. In addition, the contact surface of the longitudinal girder and seat of the tower are assigned tied constraints. Similar boundary conditions were adopted in the validated FE model of

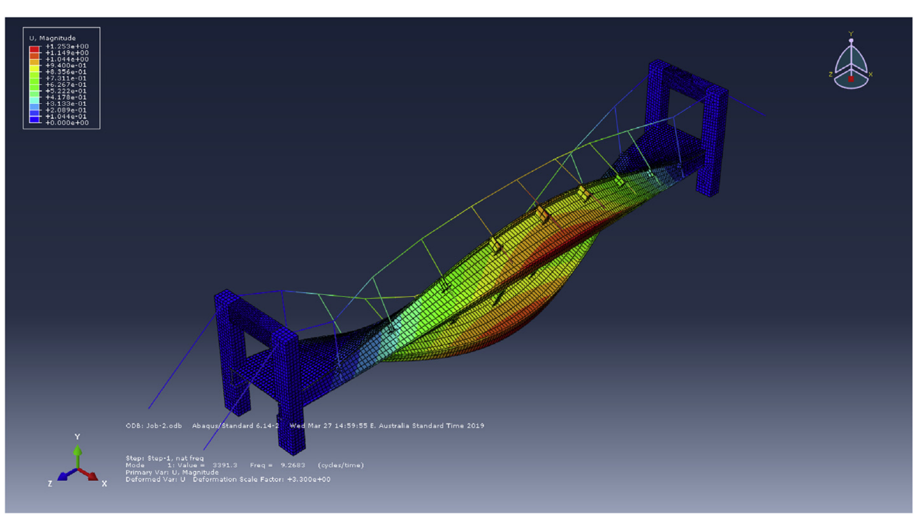
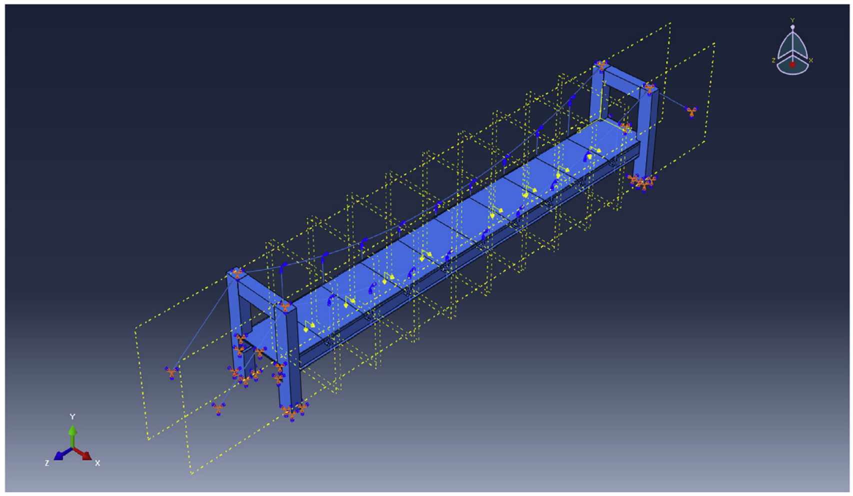
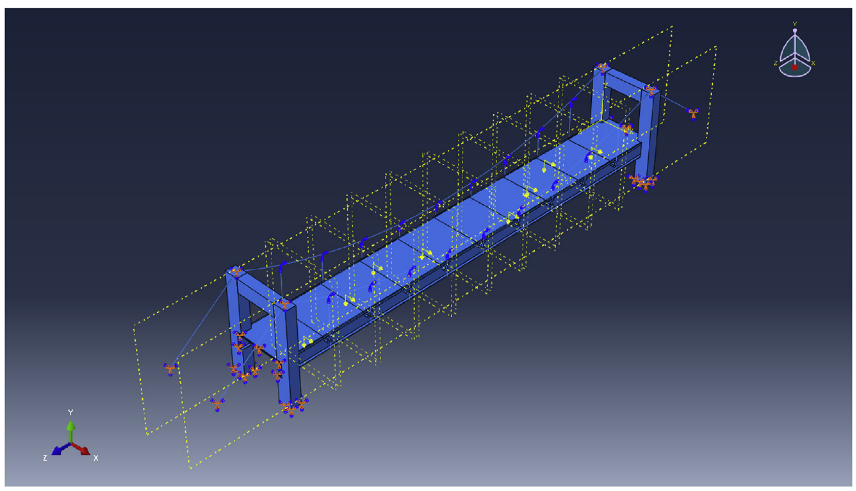


Figure 11. First natural frequency and mode shape of proposed composite bridge.



(a)



(b)

Figure 12. Simulation of normal flow of pedestrian (a) centreline movement-fast walking & running (b) dispersed movement-fast walking & running.

the Olfusá suspension bridge. The cables of the proposed pedestrian suspension bridge are prestressed with a force of 10 kN using the predefined field option of ABAQUS. Live loads of 5 kN/m^2, recommended by Euro Code [EN 1995-2] are considered over the bridge deck of the proposed suspension pedestrian bridge. Figure 9 shows the FE model of the proposed composite pedestrian suspension bridge with boundary conditions and static loading.

The static response of the proposed suspension pedestrian bridge is noted by determining the deflection and stress contours from the established FE model as illuminated in Figures 10(a) and 10(b), respectively. Figure 10(a) informs that the highest value of deflection developed at the mid span of the proposed suspension pedestrian bridge is 6.23 mm, which is much lower than the suggested peak deflection value (69 mm) of a bridge with similar span length. The maximum stress in the steel cables and hangers is around 33.7 MPa. The tensile strength of steel is 200 MPa which is much higher than these predicted stresses and so the developed suspension pedestrian bridge is safe under crowd standing condition. The selected design parameters seem to be conservative for response under static loading, but the performance under dynamic loading is yet to be evaluated.

In addition, it has been found from Figure 10(b) that the stress at GFRP layer of composite deck can be 8.43 MPa and the value is smaller than the tensile strength of recommended laminated GFRP plate (550 MPa) as provided in Table 9. The strength is 65 times higher than the predicted stress. Hence, the bridge deck composed of laminated GFRP plate will not impede the safety of the proposed suspension pedestrian bridge under high temperature/humidity scenarios, even if the laminated GFRP plate degrades and strength becomes half of the actual strength.

3.3.2. Dynamic design

The developed FE model of the innovative suspension pedestrian bridge described in the previous section is further used for the dynamic analysis. The dynamic response of the proposed suspension pedestrian bridge was evaluated by determining natural frequencies, mode shapes and accelerations under crowd movements.

3.3.2.1. Natural frequency. The fundamental natural frequency and the associated mode shape of the proposed suspension pedestrian bridge (Figure 11) are found by conducting free vibration analysis of the developed FE model of the bridge.

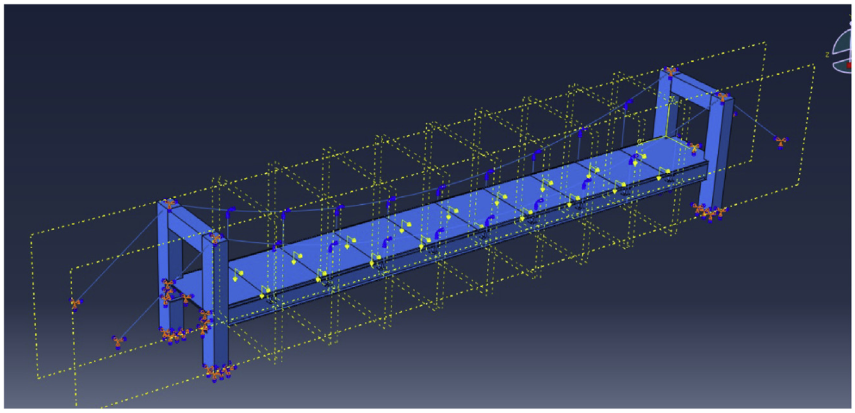


Figure 13. Simulation of dense flow of pedestrian-running in line.

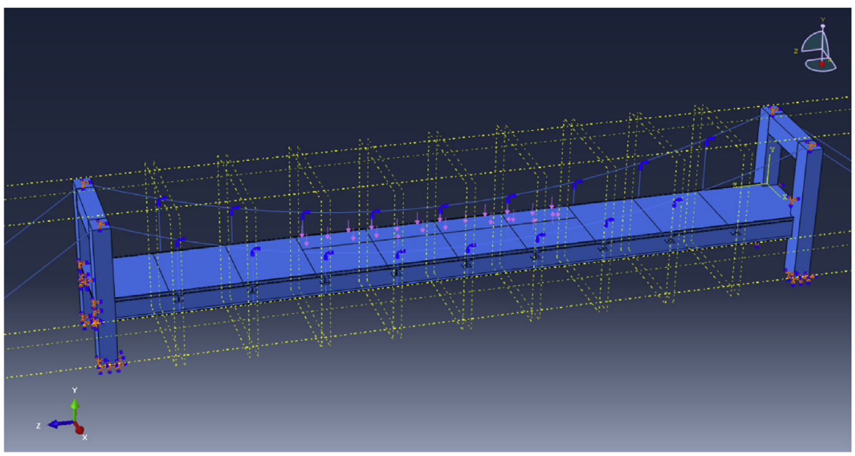


Figure 14. Pedestrian loading in peak deflected region of vibration mode.

Figure 11 shows that the first mode natural frequency is around 9.27 Hz and the mode shape is lateral-torsional. The recommended value for natural frequency is greater than 5 Hz to eliminate the probability of resonance for any pedestrian bridge. The proposed suspension pedestrian bridge therefore satisfies this criterion of the Bridge Design Code.

3.3.2.2. Acceleration. The dynamic response of the proposed suspension pedestrian bridge is monitored by determining acceleration close to the centre of the bridge by conducting FE analysis under pedestrian loads. Fast walking and running of pedestrians over the proposed pedestrian bridge deck are considered and the acceleration responses for these cases are obtained. The load amplitude during fast movement and running of pedestrians is adopted from Sa et al., [14]. The standard body weight of pedestrian is considered as a concentrated load and hence vertical and lateral force components for a single pedestrian were selected 750 N and 112 N, respectively. The accelerations were determined under three different conditions over the composite deck of the proposed suspension pedestrian bridge.

- Normal flow of pedestrian
- Dense flow of pedestrian
- Pedestrian load application at the highly deflected part of first mode shape of bridge

Normal flow of pedestrian is considered by simulating the movement of 8 pedestrians (0.1 P/m^2) over the 25 m long main span of the proposed pedestrian suspension bridge. Centre-line movement and disperse movement of pedestrians were considered (as shown in Figure 12) to determine the maximum accelerations at the top surface at the centre of the bridge deck.

Dense flow of pedestrian is considered by simulating the movement of around 1 P/2 m^2. The simulation of pedestrian movement is further continued for 18 persons (Figure 13) to observe the dynamic response of proposed bridge under dense flow of pedestrians (1P/2m^2). Accelerations at mid-span were determined considering fast walking and running conditions of pedestrians.

Table 11. Selection of layer thickness of proposed composite deck.

Layer Thickness (mm)		Maximum Deflection (mm)		Natural Frequency		First Vibration mode	Maximum Acceleration (m/s^2)	
		Max	Rec	Max	Rec		Max	Rec
GFRP-10	LG-10	6.23	69	9.27	>5	Lateral-torsional	2.50	1.52
GFRP-20	LG-20	5.42	69	9.34	>5	Lateral-torsional	**1.10**	1.52
Comment: Maximum acceleration occurs when pedestrian load is applied as pressure on the significantly deflected area of the first/lateral-torsional vibration mode							**Maximum lateral acceleration (m/s^2)**	
							Max	**Rec**
GFRP-20	LG-20	_		_		_	0.1	0.2

Pedestrian load is also applied as surface pressure over the maximum deflected part of the first mode shape following Asta et al., [18]. The selected area under a standard contributing load of pedestrians (200 Pa) for determining the maximum acceleration is shown in Figure 14.

The maximum acceleration was found for the third scenario i.e. when the pedestrian load was applied over the significantly deflected area of the first mode shape of the proposed suspension bridge. The maximum acceleration found at the top surface center of 10 mm GFRP-10 mm laminated glass composed deck was 2.5 m/s^2 which is higher than the acceleration (1.52 m/s^2) recommended by Bridge Design Code. Hence, further analysis is conducted to optimize the composite deck thickness and consequently to provide a serviceable composite deck under all types of pedestrian movement.

3.4. Optimization of composite deck

An extended FE analysis was carried out to optimize the thickness of the innovative composite deck of the developed suspension pedestrian bridge and enable the whole structure to be safe and serviceable under all types of pedestrian movement. In this analysis, the geometric properties and mechanical properties of materials of all other members of the proposed suspension pedestrian bridge the pre-stress force of the cables were kept the same as mentioned in the previous sections. The thickness of the composite deck was increased, but the other deck properties were maintained the same. Table 9 shows the summary of predicted values found from analysis results of established FE model and suggested values of Bridge Design Code for variable thicknesses of laminated GFRP plate and laminated glass of proposed composite deck.

Table 11 shows that the proposed bi-layer composite deck made up of 20 mm GFRP layer and 20 mm laminated glass layer could enable the proposed suspension pedestrian bridge to satisfy all Bridge Design Code requirements. Hence, the above deck thickness of the composite deck is recommended along with the other earlier provided geometric and mechanical properties materials of the members of proposed suspension bridge to ensure a safe and serviceable suspension pedestrian bridge.

4. Conclusions

This research work developed a new type of suspension pedestrian bridge capable of reducing vibration and acceleration under normal flow and dense flow of pedestrians. A bi-layer innovative composite bridge deck prepared with combination of laminated GFRP plate and laminated glass is proposed and the section of composite deck is optimized to improve the static and dynamic performances of the proposed pedestrian suspension bridge. Furthermore, design guidelines are provided for other parts of this bridge. Strategic design procedure was adopted along with several trials using the FE model of a medium span composite pedestrian suspension bridge. Free vibration and forced vibration analyses were carried out to evaluate the dynamic response under pedestrian loads. During forced vibration analysis, vertical and lateral movements of individual pedestrians are simulated using standard amplitudes of pedestrian walking. In addition, uniformly distributed pedestrian loads are applied over the significantly deflected area of the first mode shape of the proposed pedestrian suspension bridge. The free vibration analysis results revealed the adopted design parameters improve the natural frequency of the proposed bridge and keep it beyond the human pacing rate. After few trials during forced vibration analysis, it was found that a thickness of around 20 mm for both GFRP plate and laminated glass plate is effective to fulfill the standard bridge design code requirements for both static and dynamic responses of the proposed bridge. The information regarding design suggestions about the proposed suspension pedestrian bridge will be beneficial for introducing the similar kind of bridge in the coming years.

Declarations

Author contribution statement

Saima Ali: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

David Thambiratnam & Sabrina Fawzia: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Xuemei Liu: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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