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Parametric study on dynamic responses of stiffened sandwich composite bridge deck panel

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Abstract

Recently, the use of sandwich composites in different fields of engineering such as aerospace, marine, automobile, pipelines, bridge structure, industrial work, has attracted significant attention. Sensitivity analysis of structures made of sandwich composites is necessary to design them properly and maintain their longevity. The present study analyzes stiffened sandwich composite bridge deck panels and focuses on its sensitivity analysis. The lack of control in the manufacturing of the sandwich composites may lead to non-uniform material properties, and thus variation in its behavior. The variation in the dynamic responses obtained through the free vibration analysis of the bridge deck panel models of stiffened composites due to is studied. The free vibration analysis is implemented using a finite element method. The analysis is carried out with the stiffeners located in different positions and alignments. The glass fiber-reinforced plastic (GFRP) and polyvinyl semi-rigid foam are considered in the face and core layer for modeling the deck panels, respectively. The sensitivity of the bridge deck panels is also observed with the presence of holes of different diameters in the core layer of the sandwich composite plate without stiffeners and with a transverse stiffener. It has been noticed that dynamic response, i.e. the eigenvalue, is sensitive concerning the in-plane parameters of the face layers compared to other parameters. Moreover, an increase in the size of the hole in the core layer results in a decrease in the dynamic response of the stiffened sandwich composite bridge deck panel. The knowledge of the sensitivity of the sandwich composites will be helpful to update the model and also to design the bridge deck for better performance and improved longevity.

Keywords: Sandwich composite, Stiffened bridge deck panel, Sensitivity analysis, Natural frequency

Introduction

Recently, advanced construction materials are widely used in various civil engineering constructions. The sandwich composite plate is one of these advanced construction materials. It is also used for different fields like aerospace engineering, marine works, automobile engineering, pipelines, bridge structure, industrial work. The stiffened sandwich composite panel is widely used in bridge decks because of its advantages over the traditional bridge deck. Bridge decks are superstructures of the bridgework, which transfer all types of loads to substructures. Moreover, the stiffened sandwich composite plate can carry more loads as compared to the conventional sandwich plate. The sandwich composite plate consists of a three-layers i.e. the bottom and top layer (face layers), and the core layer. The face layer materials are fiber-reinforced plastic (FRP) and the core layer material is polyvinyl semi-rigid foam. Sensitivity analysis is needed to evaluate the uncertainty performance in structure. It helps to predict the life span of the structure and also helps to improve the structure durability, strength, and load resistance capacity. Sensitivity analysis shows the effect of variation in individual independent variables which might arise during the manufacturing of the sandwich panels or due to poor quality of materials.

Several pieces of research have been carried out on the dynamic analysis of composite structure in the last two decades. Meunier and Shenoi [1, 2] conducted the free vibration analysis for the FRP sandwich composite plate by using first and higher-order shear deformation theories and investigated the impact of the material properties and the geometry of the sandwich plate on natural frequency. It was observed that with the decrease in the ratio of core to plate thickness, the natural frequency increased. Some studies illustrate the experimental and numerical investigations [3–6] examining the behavior of FRP sandwich composites. Mandal et al. [7] determined the orthotropic property of the FRP sandwich plate with various core configurations such as triangle, circular, and rib shape. Elastic constants were calculated using the analytical method and finite element model-based software ANSYS and the results from the theoretical analysis were compared with the results from finite element models. Mondal et al. [8] investigated a sandwich composite plate, with different thicknesses of the core layer and holes of different diameters in the core layer, experimentally using the impact hammer test and numerically by finite element modal analysis. Mukhopadhyay et al. [9] studied the effect of the irregularity of the honeycomb in a sandwich panel on the natural frequency of the panel. Azarafza [10] investigated composite sandwich structures along with cores made of the stiffened grid. Experimental modal testing and numerical analysis were conducted for the sandwich structures to determine the dynamic characteristics such as frequency, damping coefficient, and mode shapes. An acceptable matching between the numerical and experimental data was observed. The effect of material properties and geometry of components of sandwich composite structures on the behavior of the sandwich composites are also illustrated in several studies [11–13].

Some literature is available on the sensitivity analysis of the FRP composite structures considering the different independent variables such as material properties, geometric structures. Thompson et al. [14] developed a reliability-based optimization technique and implemented the same to optimize the weight of the stiffened bridge deck panels of FRP composite. Sensitivity analysis was also performed to identify the design parameters. Several studies on the sensitivity analysis of sandwich composites are published in previous literature [15–17]. Mukhopadhyay et al. [18] investigated the FRP sandwich deck with a web core based on the D-optimal design to minimize the weight of the sandwich bridge decks using the Nelder-Mead simplex algorithm. Sensitivity analysis was conducted with respect to the property of materials and various geometry of the bridge deck. Santhanakrishnan et al. [19] developed a stitching technique to stitch the sandwich panels and studied their performances under a low-velocity impact test. Akoussan et al.

[20] implemented the higher-order derivative for sensitivity analysis of the damping proprieties of the sandwich structure. The sensitivity analysis was carried out for the thickness of the sandwich structure with the viscoelastic core layer. The result showed that the variation in the stiffness of the structure depends on the core thickness. Liu et al. [21] performed an analytical sensitivity analysis with respect to the static response, eigenvalues, and eigenvectors of the laminated plate and shell. Mondal et al. [22] obtained the elastic material properties of the sandwich composite plate using the inverse eigen sensitivity method (IEM) from the natural frequency with or without the presence of random noise. The IEM determined the elastic parameters in the plane or out of the plane of the face sheet of the sandwich composite plate.

Literature available on the composite structure indicates that very little research has been carried out related to stiffened sandwich deck slabs. In the present study, bridge deck panels of stiffened sandwich composites are analyzed to obtain the eigenvalues. Sensitivity analysis is performed for variation in various individual face layer material properties. Moreover, the effect of holes in the core layer of the panel is studied. The knowledge of the sensitive parameters will be helpful to control the manufacturing process as well as the quality of the stiffened sandwich composite panel.

Methodology

This study uses stiffeners at the bottom of the composite plate with different numbers and alignments, i.e., transverse, longitudinal, and inclined alignment of stiffeners. The sandwich composite deck as well as the stiffeners is made of a core layer made of polyvinyl semi-rigid foam sandwiched between two FRP face layers. Dynamic analysis is carried out to get the mode shape and natural frequency of the stiffened deck slab. A comparison study is made for the natural frequency of the sandwich composite deck panels. Sensitivity analysis is then conducted for the natural frequencies of sandwich composite plates with different positions of stiffeners with respect to various elastic parameters of face layers. In addition to this, sensitivity analysis of the stiffened sandwich deck slab is conducted concerning the holes of different diameters in the core layer of the sandwich composite plate with a transverse stiffener.

Finite element formulation of the stiffened sandwich composite plate

The sandwich plate of size 350 mm × 250 mm with the thickness of the core and face layers as 30 mm and 2.5 mm respectively is considered for the investigation as shown in Fig. 1. Glass fiber-reinforced plastic (GFRP) is considered for the face layers. Polyvinyl semi-rigid foam is considered for the core. Stiffeners are located on the bottom of the bridge deck panel with different alignments, specifically in the transverse, longitudinal, and inclined direction of the sandwich plate. This figure presents the x, y, and z-axes in the transverse, vertical, and longitudinal directions. Figure 1 shows the dimension of the sandwich composite plate without stiffener and the cross-sectional dimension of the stiffener, respectively. The typical sandwich composite plates with stiffeners (three numbers) in longitudinal, transverse, and inclined directions of the sandwich composite plate are shown in Fig. 2a–c, respectively shows a sandwich composite plate with stiffeners in the longitudinal, transverse, and inclined directions, respectively.

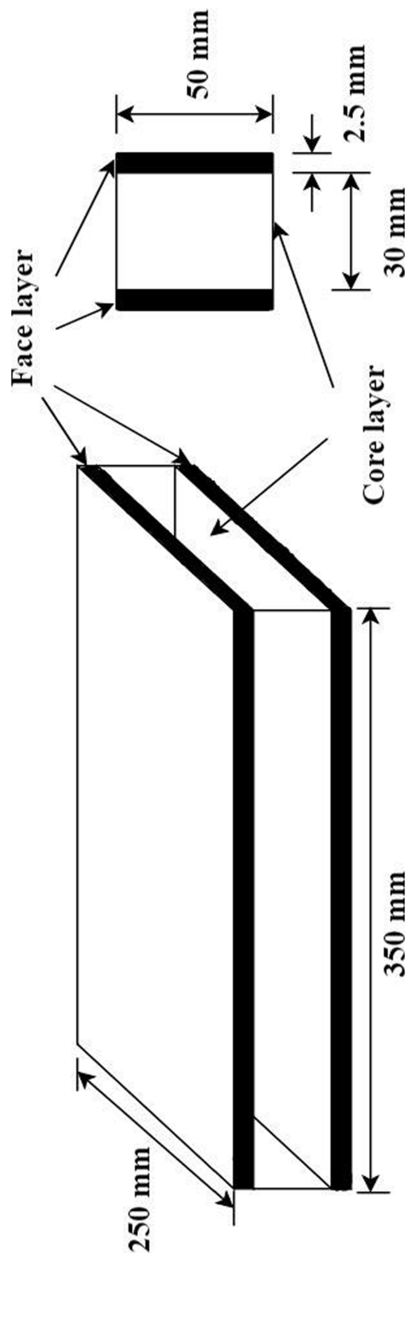

Fig. 1 Sandwich composite plate geometry and stiffener cross-section

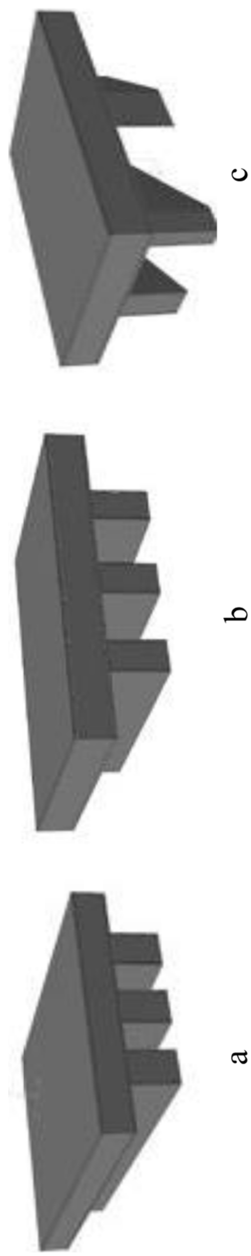

Fig. 2 Typical Sandwich composite plate with multiple stiffeners

The material constants elastic modulus chosen (as per Mondal et. al. 2015) for the face layers are $E_x = 14.46$ GPa, $E_y = 13.5$ GPa, $E_z = 60$ MPa, and Poisson's ratio are $\upsilon_{xy} = 0.32$, $\upsilon_{xz} = 0.1$, $\upsilon_{yz} = 0.1$ for the face sheets. The shear moduli are selected as $G_{xy} =$ 3.27 GPa, $G_{xz} = 5.47$ MPa, and $G_{yz} = 4.831$ MPa. The modulus of elasticity of the core layer is taken as $E = 0.119$ GPa, and the Poisson's ratio of the core layer is taken as $\upsilon =$ 0.3. The density of the core is considered to be 100 kg/m^{3,} and that of the face layers is assumed to be 1400 kg/m^3. Stiffeners considered are also sandwich composites with the same material properties as a sandwich composite. The depth of stiffener is taken as 50 mm meshing size of the sandwich composite plate is 5 mm for each layer. In the present study, 3D eight-node linear brick element (C3D8R) is considered for the sandwich composite plate. the sandwich plates without stiffeners and the plates with a single stiffener in the transverse direction are modeled with holes of different diameters in the core layer of the sandwich composite plate as well as in the stiffeners. The diameters of the holes considered are 10 mm, 15 mm, 20 mm, and 30 mm, and the spacing between in two holes is fixed to 10 mm. The typical core layers, with 15 mm diameter holes, in the panel and stiffener are presented in Fig. 3.

Numerical modeling of the plates with holes in core layers

The free vibration analysis is carried out for both sandwich composite plates with stiffener and without a stiffener in the transverse direction with the holes in core layers. The natural frequencies are mentioned in Tables 4 and 5 and from both tables, it is observed that the frequency value decreases with increasing the diameter of the hole in the core layer of the sandwich composite deck panel and stiffeners.

Free vibration analysis

The mathematical formulation for the free vibration analysis of sandwich composite bridge deck panels is briefly discussed in this section. Equilibrium equation for the stiffened sandwich composite plate can be written as

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\{y\} = \{F(t)\} \tag{1}$$

The undamped equation of motion is written in the eigenvalue problem format, as shown in Eq. 2, and is solved using an appropriate Eigen solver to obtain the frequencies and mode shapes.

$$\{[K] - \lambda_i[M]\}\{\varnothing_i\} = \{0\} \tag{2}$$

Here, $\lambda_i=\omega_i^2$ is the eigenvalue, ω is the frequency of the structure, and ϕ_i is the corresponding eigenvector (mode shape). The terms $[K]$ and $[M]$ represent the global stiffness and mass matrix of the sandwich composite plate. The global stiffness matrix $[K]$ includes the contribution of the two face sheets and the core and can be defined as the addition of elemental stiffnesses of individual layers as shown in Eq. 3. The global mass matrix can be obtained using Eq. 4.

$$[K] = \left[K^{top}\right] + \left[K^{core}\right] + \left[K^{bot}\right] \tag{3}$$

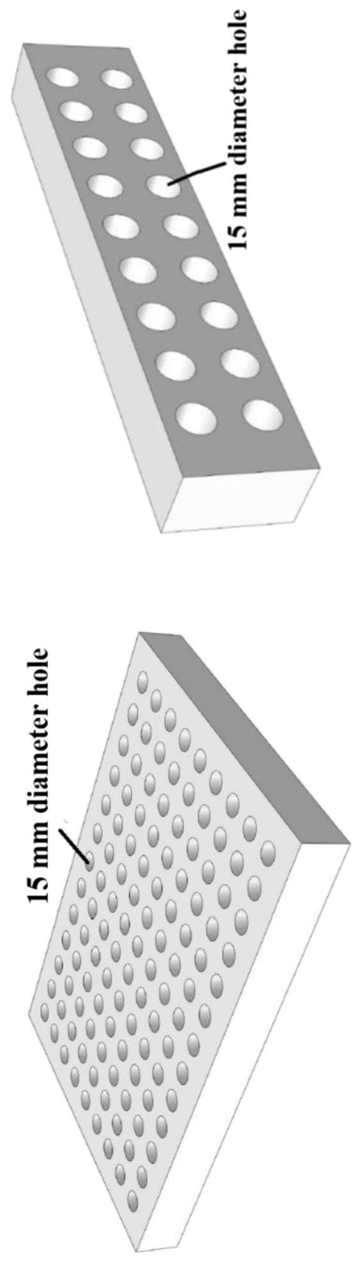

Fig. 3 A typical sandwich core of bare panel and core of the stiffener with holes of 15 mm diameter

Table 1 The natural frequency of the plates with the different alignment of stiffeners

Natural frequency (cycle/time) for the bridge deck panels										
Mode	**CSWS**	**CS1TS**	**CS2TS**	**CS3TS**	**CS1LS**	**CS2LS**	**CS3LS**	**CS1IS**	**CS2IS**	**CS3IS**
1	128.4	136.66	126.7	133.36	143.62	132.68	145.15	203.82	170.48	186.69
2	312.45	396.24	501.31	522.85	296.48	240.74	237.9	412.69	302.05	380.9
3	387.43	414.1	520.81	542.05	358.39	339.06	327.64	433.02	376.44	390.19
4	767.73	721.13	680.07	668.67	556.04	583.19	467.14	670.46	629.67	598.99
5	817.42	772.52	712.53	674.63	605.18	616.2	526.59	686.41	640.31	617.36
6	818.71	777.49	741.89	675.82	827.21	691.79	683.52	804.07	656.8	633.07
7	849	825.12	862.89	807.28	852.42	826.79	795.42	841.19	694.32	699.13
8	851.04	837.88	923.03	859.56	865.01	839.2	806.65	864.62	789.57	753.68
9	910.41	868.49	940.49	915.3	934.52	882.47	869.42	893.99	829.27	765.7
10	985.87	898.14	957.9	923.37	957.82	890.55	882.31	923.15	869.39	806.38

Table 2 Case details for sandwich composite plates with the different alignment of stiffeners

Case explanation	Name of case	Mass (kg)
Composite sandwich without stiffeners	CSWS	0.87
Composite sandwich with one transverse stiffener	CS1TS	1.00
Composite sandwich with two transverse stiffeners	CS2TS	1.12
Composite sandwich with three transverse stiffeners	CS3TS	1.25
Composite sandwich with one longitudinal stiffener	CS1LS	1.05
Composite sandwich with two longitudinal stiffeners	CS2LS	1.22
Composite sandwich with three longitudinal stiffeners	CS3LS	1.40
Composite sandwich plate with one inclined stiffener	CS1IS	1.07
Composite sandwich with two inclined stiffeners	CS2IS	0.89
Composite sandwich with three inclined stiffeners	CS3IS	1.09

$$[M] = [M]^{top} + [M]^{core} + [M]^{bot} \tag{4}$$

Where, $[K^{top}]$, $[K^{bot}]$, and $[K^{core}]$ represent the element stiffness matrices of the top, bottom, and core layer, respectively. Similarly, $[M]^{top}$, $[M]^{bot}$, and $[M]^{core}$ are the element mass matrices of the top, bottom, and core layer of the sandwich composite panel, respectively.

Result and discussion

Free vibration analysis is carried out for the stiffened sandwich composite bridge deck panels. The first ten-mode natural frequencies of the sandwich composite plate without stiffener and with stiffeners are obtained, mentioned in Table 1, by free vibration analysis. The nomenclatures along with the masses of the models are mentioned in Table 2. From the free vibration analysis, corresponding mode shapes are also drawn. The first five-mode shapes for the sandwich plates with multiple stiffeners are demonstrated in Figs. 4, 5, and 6.

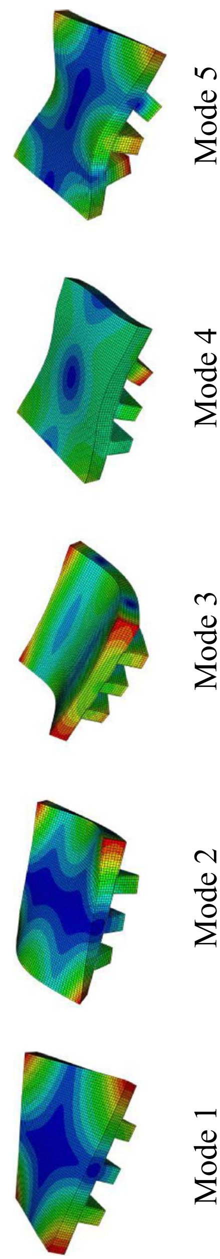

Fig. 4 Mode shape of the sandwich composite plate (three stiffeners in the transverse direction)

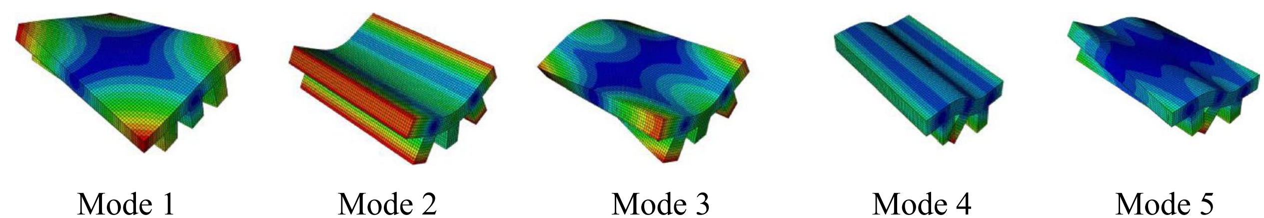

Fig. 5 Mode shape of the sandwich composite plate (three stiffeners in the longitudinal direction)

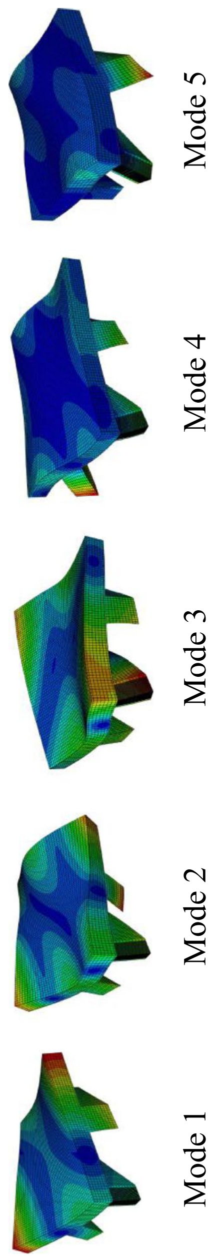

Fig. 6 Mode shape of the sandwich composite plate (three stiffeners in the inclined direction)

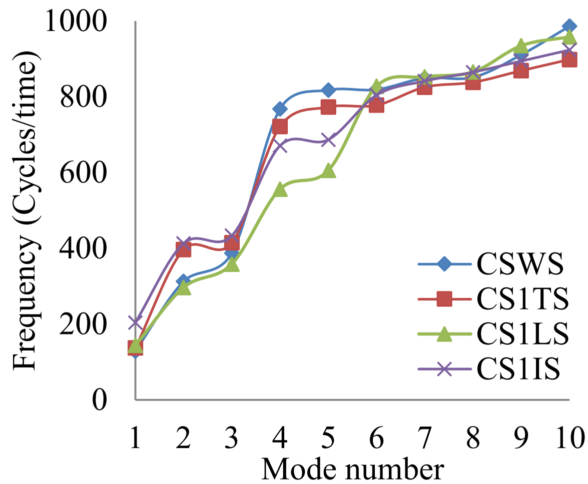

Fig. 7 Comparison of frequencies of the plates with single stiffener

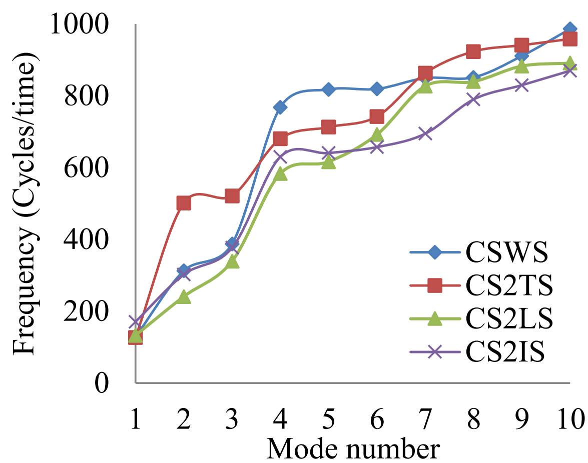

Fig. 8 Comparison of frequencies of theplates with two stiffeners

Comparison study of dynamic responses of stiffened sandwich composite plates

A comparison study of natural frequencies is carried out for the sandwich composite plate models. Firstly, the comparison is carried out for the plates with the different alignment of stiffeners keeping the number of stiffeners constant. The comparison of frequencies between the sandwich composite plate without stiffener and with a single stiffener in transverse, longitudinal, and inclined direction is shown in Fig. 7. It is observed that for the first three modes, the inclined stiffened sandwich composite plate gives higher frequency values. The sandwich composite deck without stiffener gives higher frequency values for the next three (4–6) modes. For the 7th to 10th modes, the longitudinal stiffened sandwich composite deck gives higher frequency values as compared to all other models. However, the difference between the frequency values for a particular mode is low.

The comparison of frequencies for the cases CSWS, CS2TS, CS2LS, and CS2IS is presented in Fig. 8. Higher frequency is observed in the first three and 8th to 10th modes

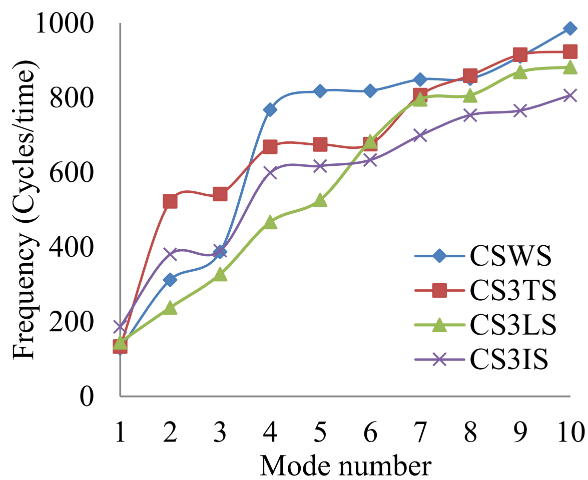

Fig. 9 Comparison of frequencies of the plates with three stiffeners

Table 3 Case details for the sandwich composite plates with holes in core layers

Case explanation	Name of case
Sandwich plates without stiffeners and holes	WS-WH
Sandwich plates without stiffeners but with 10 mm holes	WS-H10
Sandwich plates without stiffeners but with 15 mm holes	WS-H15
Sandwich plates without stiffeners but with 20 mm holes	WS-H20
Sandwich plates without stiffeners but with 30 mm holes	WS-H30
Sandwich plates with a transverse stiffener and without holes	TS-WH
Sandwich plates with a transverse stiffener and with 10 mm holes	TS-H10
Sandwich plates with a transverse stiffener and with 15 mm holes	TS-H15
Sandwich plates with a transverse stiffener and with 20 mm holes	TS-H20
Sandwich plates with a transverse stiffener and with 30 mm holes	TS-H30

Table 4 Frequencies of the sandwich plate without stiffener and with holes in the core layer

Natural frequency (cycle/time) for the bridge deck panels					
Mode	**WS-WH**	**WS-H10**	**WS-H15**	**WS-H20**	**WS-H30**
1	128.40	104.32	93.984	86.314	78.368
2	312.45	273.16	263.08	251.39	240.26
3	387.43	332.62	316.78	301.15	289.27
4	767.73	629.8	537.03	464.75	379.53
5	817.42	669.53	642.52	590.77	497.11
6	818.71	713.06	658.59	612.06	572.18
7	849.00	772.43	689.29	657.41	597.29
8	851.04	775.83	719.35	681.30	623.40
9	910.41	777.49	723.66	697.77	626.65
10	985.87	821.08	758.76	743.02	635.58

Table 5 Frequency of the sandwich plate with a transverse stiffener and with holes in the core layer

Natural frequency (cycle/time) for the bridge deck panels					
Mode	**TS-WH**	**TS-H10**	**TS-H15**	**TS-H20**	**TS-H30**
1	136.66	112.48	103.42	95.931	85.199
2	396.24	341.04	327.32	310.66	295.38
3	414.10	363.97	337.73	337.28	306.52
4	721.13	606.52	522.80	458.10	372.90
5	772.52	624.27	565.6	503.34	424.48
6	777.49	699.98	666.61	617.88	550.11
7	825.12	719.34	684.78	624.81	562.95
8	837.88	722.36	697.81	664.91	596.62
9	868.49	744.68	711.15	684.39	628.42
10	898.14	804.58	774.32	702.51	631.67

Table 6 Natural frequencies for the CS1TS after increasing 5% of face layer elastic parameters

	Natural frequency (cycle/time) due to 5% increment of elastic parameters									
Mode	**CS1TS**	E_x	E_y	E_z	υ_{xy}	υ_{xz}	υ_{yz}	G_{xy}	G_{xz}	G_{yz}
1	136.66	136.66	136.66	136.67	136.66	136.66	136.66	136.68	136.88	136.73
2	396.24	396.25	396.24	397.49	396.24	396.25	396.24	396.27	396.48	396.32
3	414.10	414.37	414.1	415.39	414.10	414.17	414.10	414.13	414.18	414.58
4	721.13	725.88	721.13	721.18	721.13	721.2	721.13	721.18	721.31	721.85
5	772.52	777.59	772.52	772.52	772.53	772.52	772.52	772.54	772.52	772.52
6	777.49	780.58	777.50	777.53	777.50	777.50	777.49	777.54	777.89	777.71
7	825.12	825.14	825.12	828.58	825.12	825.16	825.12	825.15	825.31	825.19
8	837.88	839.36	837.88	839.94	837.88	837.8	837.88	837.92	838.05	838.6
9	868.49	870.53	868.49	869.77	868.49	868.64	868.49	868.53	868.79	869.19
10	898.14	903.05	898.14	898.87	898.15	898.06	898.14	898.19	898.33	898.45

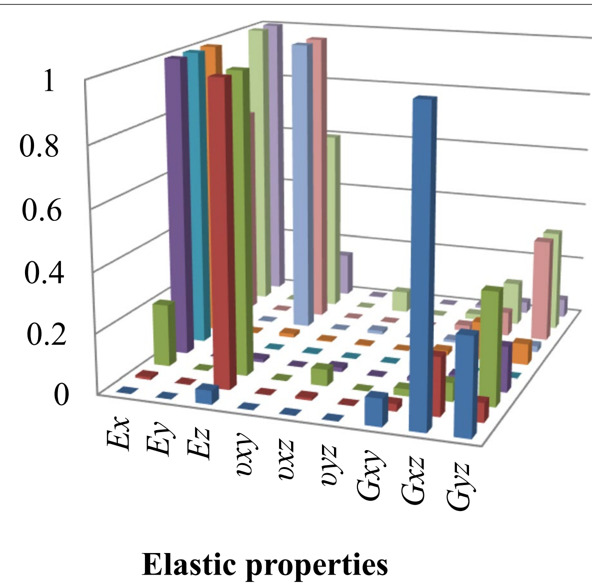

Fig. 10 Sensitivity analysis for CS1TS

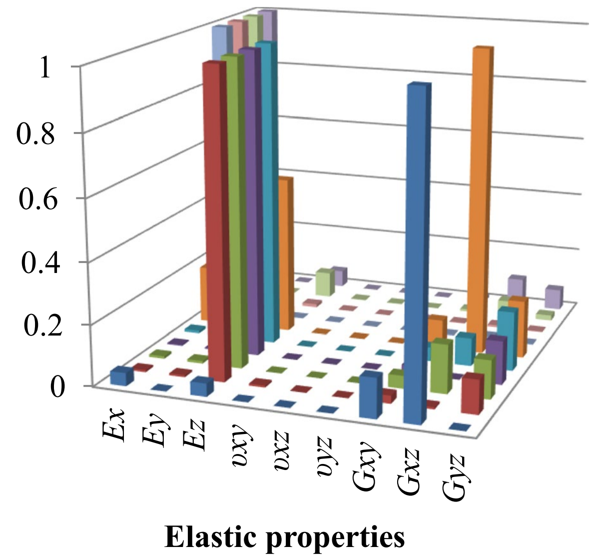

Fig. 11 Sensitivity analysis for CS1LS

of the sandwich composite plate with two stiffeners in the transverse direction. Figure 9 shows the comparison of frequencies between the plate models CSWS, CS3TS, CS3LS, and CS3IS. The sandwich plate CS3TS is observed to have higher frequencies in the 2nd and 3rd modes. A little difference between the frequencies of plates CSWS and CS3TS is observed. It has been noticed the sandwich composite plate with transverse stiffeners performed better with relatively higher frequencies. Moreover, it is also observed that the plates with multiple stiffeners give better results. The increase in the performance of the sandwich composite panels can be observed because of the added stiffness by the stiffeners.

From the overall comparison study, it is observed that the plate models with stiffeners in the transverse direction performed better as compared to other cases and the plate models with one stiffener (CS1TS) in different directions give better-performing results with higher frequency values. The nomenclature for the sandwich composite plates (with

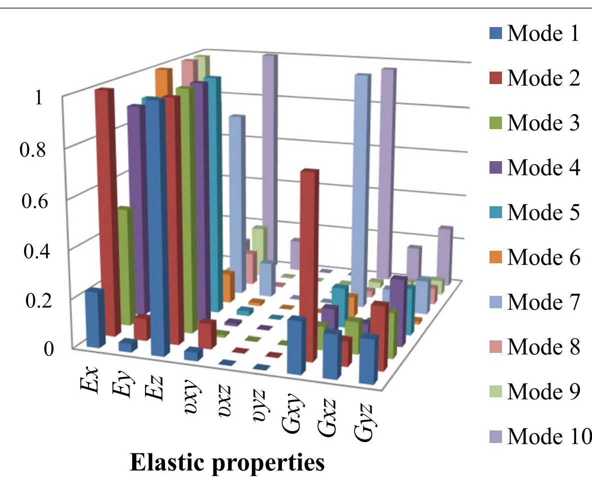

Fig. 12 Sensitivity analysis for CS1IS

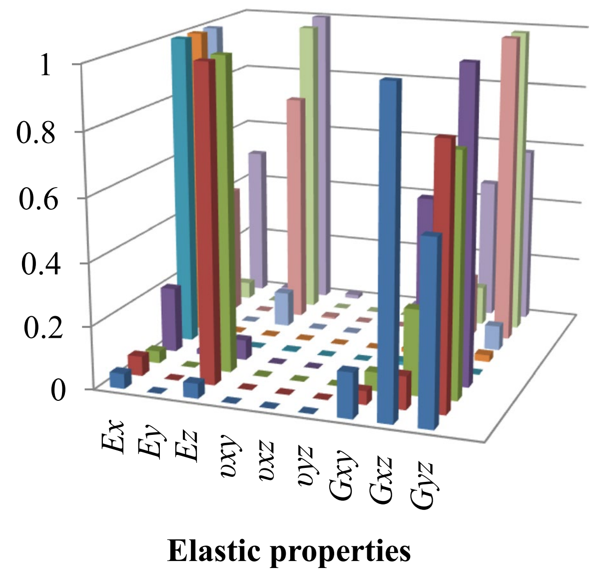

Fig. 13 Sensitivity analysis for CS2TS

holes in the core layer) without stiffener and with a transverse stiffener is presented in Table 3. The natural frequencies for the sandwich plate CSWS and CS1TS with holes in the core are obtained and presented in Tables 4 and 5, respectively.

Sensitivity analysis of sandwich plates without holes w.r.t elastic parameters

Sensitivity analysis is carried out for all the cases by a 5% increment of the elastic properties of the individual face layer. The free vibration analysis is performed for the plates with increasing elastic parameters of the face layers to determine the first ten-mode natural frequencies for all the cases. Table 6 represents the natural frequencies of the plate

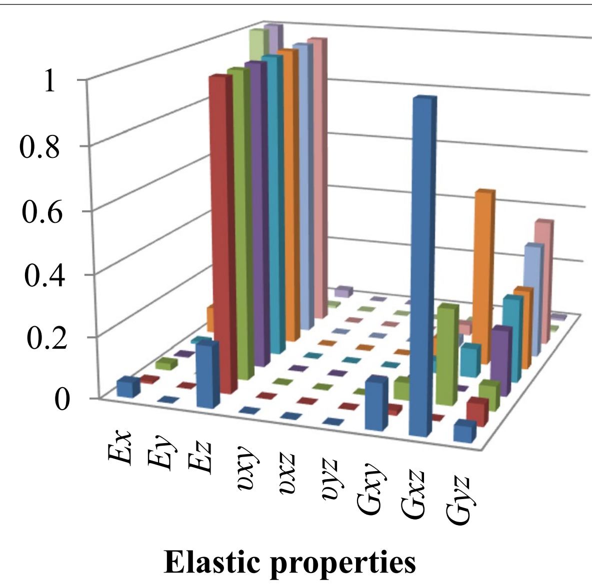

Fig. 14 Sensitivity analysis for CS2LS

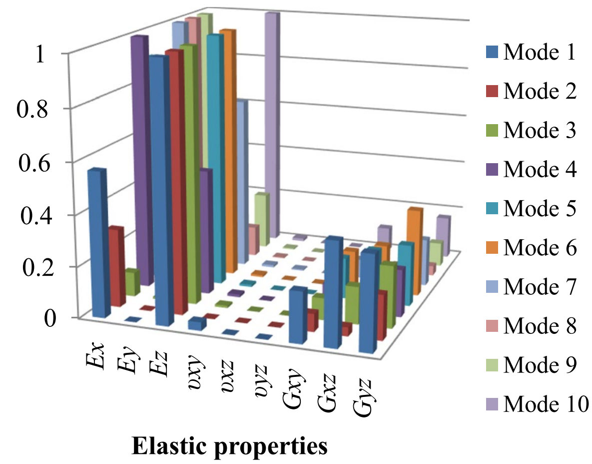

Fig. 15 Sensitivity analysis for CS2IS

with a single stiffener in the transverse direction with a 5% increment in the individual elastic parameters.

The sensitivity analysis for the above case and normalized value is shown in Fig. 10. It can be observed that the in-plane Young's modulus in x and z direction (E_x and E_z) of the bridge deck panel are more sensitive as compared to all other elastic parameters. Similarly, sensitivity analysis for the case CS1LS is carried out, and it is observed that E_x and E_z are more sensitive. Moreover, the shear modulus G_{xz} is also observed to be a sensitive parameter as shown in Fig. 11. The sensitivity for the face layer elastic parameters for the case CS1IS is shown in Fig. 12. The in-plane elastic modulus (E_x, E_z) and shear modulus G_{xy} are found to be more sensitive as compared to other elastic parameters.

Accordingly, the sensitivity analysis is performed for the sandwich composite panels with multiple stiffeners at their bottom. Figure 13 shows the sensitivity analysis for the

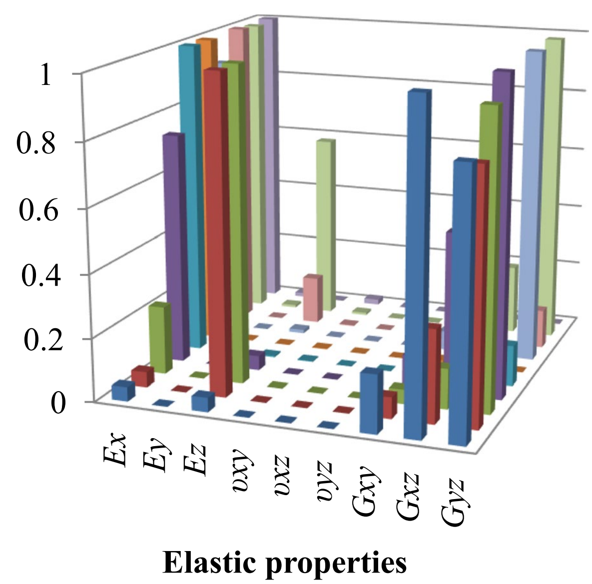

Fig. 16 Sensitivity analysis for CS3TS

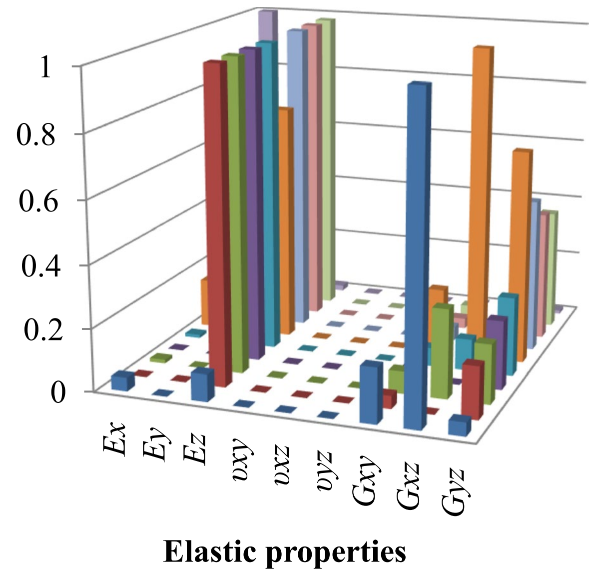

Fig. 17 Sensitivity analysis for CS3LS

case CS2TS and it is observed that E_x and E_z are significantly sensitive. The shear modulus G_{xz} and G_{yz} are also noticed to be sensitive.

The sensitivity of the elastic parameters for the case CS2LS and CS2IS are shown in Figs. 14 and 15, respectively. It is noticed that E_z is highly sensitive in the first eight modes compared to E_x for the plate CS2LS. The shear modulus G_{xz} and G_{yz} are also observed to be less sensitive in comparison to the in-plane elastic moduli. For the plate CS2IS, the elastic modulus E_x and E_z are highly sensitive. The shear moduli G_{xy}, G_{xz}, and G_{yz} are found to be moderately sensitive as compared to the in-plane Young's moduli. The sensitivity analysis for the sandwich composites plates (with multiple stiffeners) CS3TS, CS3LS, and CS3IS are presented in Figs. 16, 17, and 18, respectively. It has been observed that the in-plane elastic moduli E_x and E_z are sensitive. However, the shear moduli are comparably less sensitive than in-plane elastic properties.

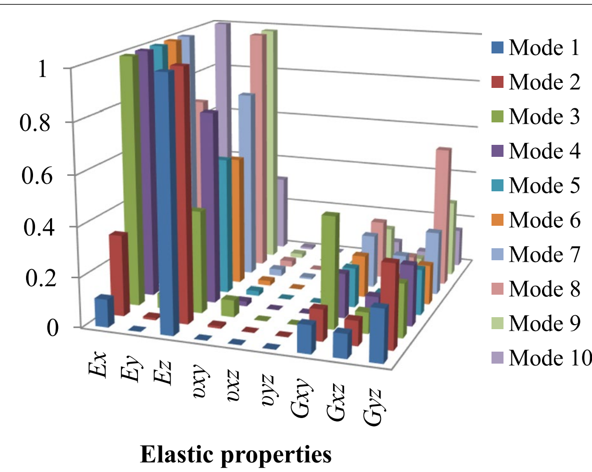

Fig. 18 Sensitivity analysis for CS3IS

Table 7 Natural frequencies for the WS-H10 after increasing 5% of face layer elastic parameters

Mode	Natural frequency (cycle/time) due to 5% increment of elastic parameters									
	WS-H10	E_x	E_y	E_z	υ_{xy}	υ_{xz}	υ_{yz}	G_{xy}	G_{xz}	G_{yz}
1	104.32	104.33	104.32	104.33	104.32	104.32	104.32	104.35	104.63	104.33
2	273.16	273.16	273.16	275.11	273.16	273.16	273.16	273.18	273.16	273.17
3	332.62	332.62	332.62	334.18	332.62	332.62	332.62	332.65	332.93	332.63
4	629.80	629.87	629.80	629.82	629.80	629.80	629.80	629.83	630.52	629.84
5	669.53	669.54	669.53	674	669.53	669.53	669.53	669.57	669.53	669.56
6	713.06	713.08	713.06	717.19	713.06	713.06	713.06	713.12	713.31	713.1
7	772.43	776.66	772.43	772.44	772.43	772.43	772.43	772.58	772.51	772.44
8	775.83	779.19	775.83	775.85	775.83	775.83	775.83	775.88	776.66	775.98
9	777.49	784.03	777.49	777.5	777.49	777.49	777.49	777.63	777.64	777.51
10	821.08	826.28	821.08	821.76	821.09	821.08	821.08	821.22	821.39	821.11

Sensitivity analysis for the sandwich composite plate with holes in core layers w.r.t elastic parameters

Sensitivity analysis is carried out for the sandwich composite plates with holes of diameter 10 mm and 20 mm in the core layer of sandwich composite plates without stiffener and with a transverse stiffener w.r.t a 5% increment of the elastic parameters. The natural frequencies for the sandwich plate WS-H10 with a 5% increment of individual elastic properties of face sheets are shown in Table 7.

The sensitivity analysis of the sandwich composite plates WS-H10 and WS-H20 are shown in Figs. 19 and 20, respectively, which describes that in-plane parameters E_z, E_x, and G_{xz} are sensitive compared to other elastic parameters. Similarly, Figs. 21 and 22 represent the sensitivity in the sandwich composite plates TS-H10 and TS-H20, respectively. It is observed that the E_x, E_z, and G_{xz} are sensitive parameters to the natural frequency of the sandwich composite plate. However, the other shear moduli G_{xy} and G_{yz} are also observed to be moderately sensitive.

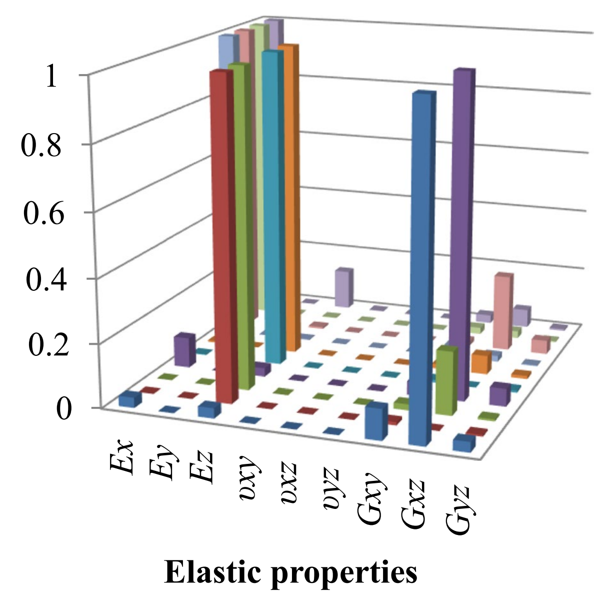

Fig. 19 Sensitivity analysis for WS-H10

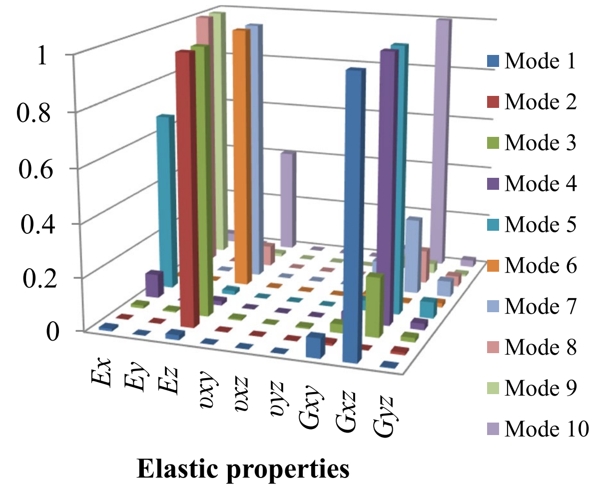

Fig. 20 Sensitivity analysis for WS-H20

Sensitivity analysis of sandwich plates with holes w.r.t the size of the holes

The sandwich composite plates with transverse stiffeners are modeled with holes of different diameters in the core layer of the deck panel as well as stiffeners. The natural frequencies of all the cases with holes are mentioned in Tables 3 and 4. A sensitivity analysis is carried out for all the cases by the normalization of the natural frequencies.

It is observed that the plates with 30 mm diameter holes in the core layers give decreased natural frequency values showing that the size of the holes is also a sensitive parameter. The sensitivity analysis is conducted for the plates with and without transverse stiffeners and with holes in the core layer. The sensitivity for the cases WS-H10, WS-H15, WS-H20, and WS-H30 is shown in Fig. 23. The sensitivity for the

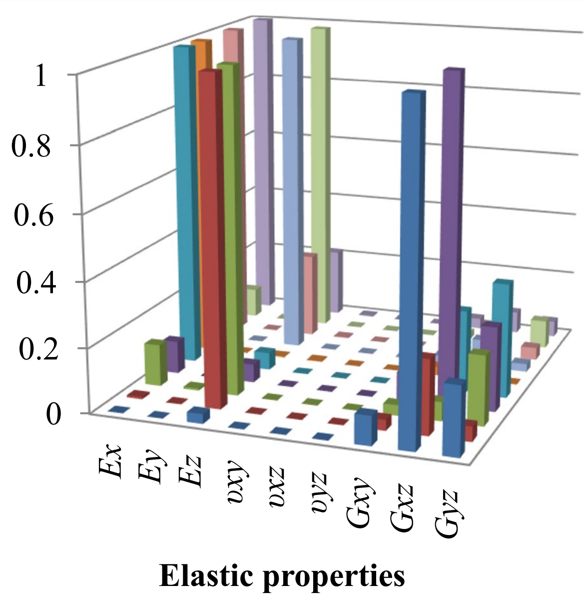

Fig. 21 Sensitivity analysis for TS-H10

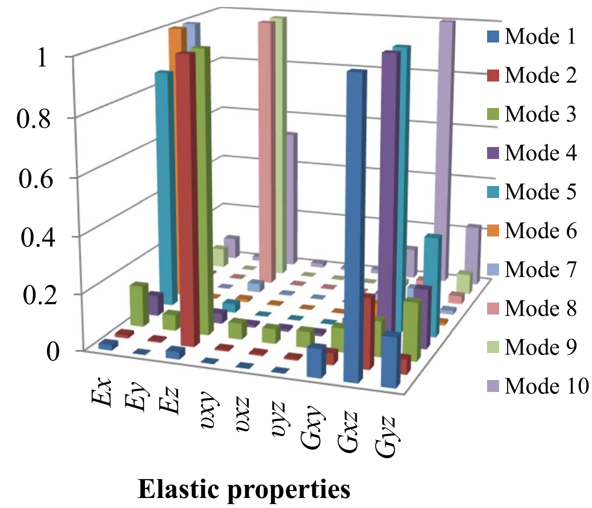

Fig. 22 Sensitivity analysis for TS-H20

cases TS-H10, TS-H15, TS-H20, and TS-H30 is shown in Fig. 24. It can be observed that for larger dia holes (e.g., 30), all modes are equally sensitive for a plate with transverse stiffeners and without stiffeners. However, for smaller dia holes, sensitivity can be observed for a plate with transverse stiffeners.

Conclusion

The present study performed the dynamic analysis of a sandwich plate with and without stiffeners. The stiffeners are provided along a transverse, longitudinal, and inclined direction at the bottom of the panel surface of the sandwich composite bridge deck. The sensitive analysis has been performed for various scenarios, e.g., sensitivity analysis with respect to the alignment of stiffeners, individual materials properties, and hole diameter in the core layers. A comparison study of eigenvalues concludes that the

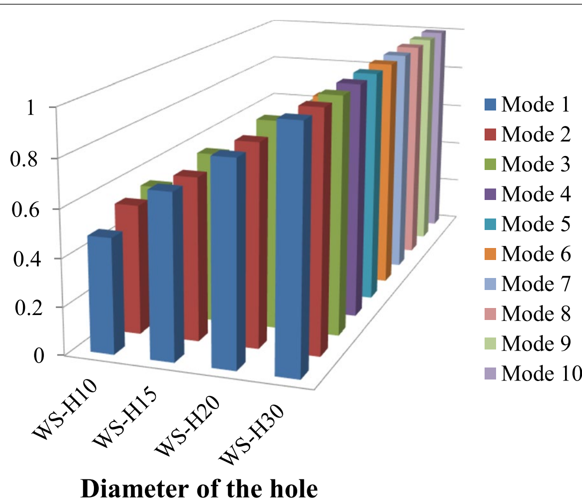

Fig. 23 Comparison of frequencies for the plates without stiffener but with holes

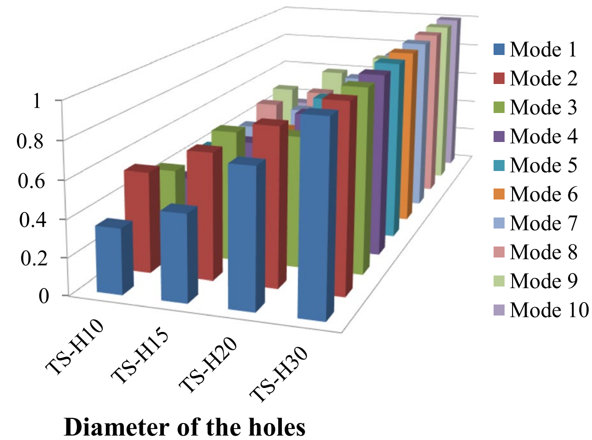

Fig. 24 Comparison of frequencies for the plates with a transverse stiffener and with holes

sandwich composite deck with transverse stiffeners shows a good result with higher eigenvalues as compared to other stiffened sandwich composite bridge deck panels. It is noticed that the in-plane elastic parameters E_x and E_z are more sensitive as compared to all other elastic parameters in all stiffened sandwich composite bridge decks. Besides, the shear moduli are less sensitive as compared to Young's moduli, but G_{xz} is sensitive than the other two shear moduli. Moreover, sensitivity analysis with different hole sizes in the core layer of the sandwich composite plate without stiffener and with a single transverse stiffener. It is observed that natural frequencies are sensitive for smaller dia holes present in the core. The repeated real-life experiment is very time-consuming and costly. On the other hand, accurate finite element modeling gives satisfactory results and is accepted worldwide. The work emphasizes that the sensitivity analysis performed numerically with respect to different parameters is a better alternative in comparison to full-scale modeling and updating all parameters. The result will also provide insights to design the sandwich composite structures for economic and improved performance.

Nomenclature

E_x Modulus of elasticity of face layers in the x-direction
E_y Modulus of elasticity of face layers in the y-direction
E_z Modulus of elasticity of face layers in the z-direction
υ_{xy} Poisson's ratio of face layers in the xy plane
υ_{xz} Poisson's ratio of face layers in the xz plane
υ_{yz} Poisson's ratio of face layers in the yz plane
G_{xy} Shear modulus of face layers in the xy plane
G_{xz} Shear modulus of face layers in the xz plane
G_{yz} Shear modulus of face layers in the yz plane
E Modulus of elasticity of core layer
υ Poisson's ratio of the core layer
x, y, *and* z Cartesian axis directions

Abbreviations
FRP: Fiber-reinforced plastic; GFRP: Glass fiber-reinforced plastic; GPa: Giga-pascal; MPa: Mega-pascal.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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