Dynamic performance of sandwich composite plates with circular hole/cut-out: A mixed experimental–numerical study

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Abstract

The dynamic characteristics of sandwich composite plates with holes at various locations are investigated both experimentally and through numerical simulations. The critical parameters which affect the natural frequencies of such plates with holes or cut-outs are the core and face sheet thicknesses, diameter and location of the holes and aspect ratio of the plate. A rigorous parametric study has been conducted to determine their interrelationship and presented in a concise manner. An experimental investigation has been conducted in the beginning to get an idea about the variations of the above mentioned parameters. The results can be utilized to determine the changes in dynamic characteristics of sandwich composite plates with holes with specified diameters and locations. The methodology can also be useful to control the dynamic responses of such plates by incorporating holes of chosen diameters at appropriate locations. The results may be used to create design curves for satisfactory dynamic performances of sandwich composite plate with holes.

1. Introduction

Sandwich composite plates are being increasingly utilized as different components of the marine, aerial and terrestrial structures. Cut-outs/holes are also a requirement in these structures primarily for the purpose of making the structure lighter, for venting and inspection, for providing a passage for service facilities like cables, fuel pipes etc., for fastening/mounting other structural members and/or instruments using bolts and rivets. It is quite obvious that the introduction of a hole/cut-out will result in shifts of natural frequencies, as well as changes in mode shapes of the plates and thereby would eventually change the dynamic response characteristics of the structure. It is also conceivable that the sensitivities of these changes will largely vary with the location, shape and size of such holes/cut-outs. Even though there exists a large body of literature investigating these effects for cases of laminated composites; there appears to be no literature (to the best of the authors' knowledge) investigating the effects of hole/cut-out on the dynamic performance of sandwich composites. It should be pointed out in this regard that sandwich composite panel differs significantly from a laminated composite plate since sandwich panel consists of a “soft” foam core separating the laminated composite face sheets. In fact, the primary advantage of these sandwich panels is low weight to high strength ratio which has made them to be indispensable components in modern designs of aerospace and marine vehicular structures.

Since, there exists no literature on the effects of hole/cut-out on the dynamic performance of sandwich composite plates; a brief literature survey is presented for laminated composite plates with holes/cut-outs and their effects on dynamic performance. Brief literature survey is also presented for determination of dynamic performance of sandwich composite panels without holes using modal testing and analysis.

There is an extensive set of literature concerned with determination of stresses near the hole/cut-out regions in a laminated composite panel subjected to different types of loading scenarios. Examples include-axial in-plane loads [1] or thermal loads [2] resulting in global buckling of the plate or micro buckling of the fibers [3], free and forced vibration studies with different boundary conditions [4–8], effects of numerous numbers of hole within a plate subjected to various loading conditions [9]. Since holes/cut-outs result in stress concentration and eventually turn out to be the influential parameters for the design purpose, researchers have used various closed form solutions [10] as well as developed different types of finite elements using various assumptions related to plate theories, such as Rayleigh–Ritz method [11] equivalent single layer (ESL) theory and multilayer
theory [12] etc. Investigations have been carried out for plates with different damage criterions to accurately measure stresses near the holes/cut-outs subjected to different loading scenarios. Optimum placement of holes/cut-outs in laminated composite panels has also been investigated [13]. With regards to modal testing of sandwich composite panels, there exist experimental and numerical studies in which the influence of material properties of the core and the face-sheet (including its layup and orientation) were investigated [14–20] and found to be significant.

Most recently, researchers [21,22] has performed experimental and numerical investigations on large amplitude non-linear vibration of laminated and sandwich composite rectangular plates with free edges using laser Doppler vibrometer. Zippo et al. [23] conducted experimental investigations on active control of rectangular sandwich composite plate with carbon fibre reinforced polymer outer skins and a polymer paper core under free boundary conditions.

However, there appears to be a lacuna in literature with regards to the effect of holes/cut-outs on the dynamic performance of sandwich composite plates. This issue has been investigated and presented in this paper through a coordinated experimental and numerical investigation by varying numerous factors such as the diameter and position of the hole, the thickness of the face sheet and the core and also aspect ratio of the plate. The effect of these variations on the dynamic performance of the sandwich composite plates are then observed and discussed upon.

Details of the process of manufacture of the sandwich composite plate, as well as the experimental modal testing procedures are provided in Section 2. Section 3 presents development of a representative numerical model for sandwich composites by validating it with experimental results. Section 4 contains numerical parametric studies in which the diameter of the hole as well as its position is varied to arrive at various conclusions related to the changes in natural frequencies for different core and face-sheet thicknesses. Section 5 provides discussions about the results obtained followed by Section 6 which concludes the investigations with critical observations.

2. Experimental investigations

2.1. Manufacture of sandwich composite plate

Closed cell semi-rigid PVC foam of mass density 100 kg/m$^3$, having approximate cell size of 400 μm (manufactured by DIAB Inc. and marketed by the trade name of Divinycell H100) was utilized as the core material for the sandwich composite construction. The foam was sandwiched between two glass fibre reinforced epoxy matrix face sheets. The face-sheets typically comprise of two alternate layers of Woven Roving glass fibre mats (with 276 number of threads per meter as warp and 237 threads per meter as weft at 90° angle) stitched and assembled with Chopped Strand glass fiber mat and 1.3 mm thick resin treated plain Woven Roving glass fiber mat (552 threads as warp and 276 threads as weft at 90° angle). For experimental purpose the thickness of the core considered for sample fabrication was 30 mm and that of the face sheet was 2.5 mm on either side. EPIKOT resin 828 LVEL with the anhydride hardener EPIKURE curing agent 866 and the accelerator EPIKURE catalyst 101 of Momentive Specialty Chemicals (“Momentive”), Ohio, USA were used for the vacuum resin infusion work. The resin, hardener and catalyst at the ratio of 100:80:1.5 by weight were mixed and stirred for 15 min at 150 rpm to eventually make the resin mix system. The resin mix was infused through the preform (face sheet and core sandwich) covered by porous Teflon film and highly permeable breather cloth primarily through vacuum alone. Upon complete part wetting, the infusion lines were blocked and the full assembly was vacuum cured at room temperature for at least 40 h. The final fabricated plate sample having dimension of 400 mm × 300 mm was then utilized for modal testing experiments. Once the modal testing was completed for a sandwich plate, a concentric hole of 100 mm was drilled and the sample was again modal tested. The same sample with 100 mm hole was again drilled to obtain 150 mm and then a 200 mm hole and modal testing was performed. The same plate was considered for all the cases – without any hole and then subsequently, plate with 100 mm, 150 mm and 200 mm drilled holes. This is done to eliminate the possibility of any inaccuracy arising out of the variations in properties (due to manufacturing of the plates) had there been different plates with the specified holes. For each set of experiments at least 3 samples were tested prior to reporting of any observation which has been made, based on the mean of the results obtained from experimental investigations.

2.2. Modal testing of sandwich composite plates

The modal testing investigations were carried out on sandwich composite plates with and without cut-outs using an instrumented impact hammer (type 8206-002 of Bruel & Kjaer) to excite the plates and IEPE accelerometer (DeltaTron 4507 of Bruel & Kjaer) to measure the accelerations. A spectrum analyzer (3560-C-L4 of Bruel & Kjaer) [24] was used to conduct the Fast Fourier Transform of the acquired force and response signals measured in time domain. The quality of the FRF measurements were checked using the Coherence function (0–1, 1 for perfect causality) whether the system output is caused by the system input or by other factors, e.g. noise, nonlinearity etc. Small tabs of dimensions 20 mm × 20 mm × 30 mm with holes are attached to the core portion of the plate at the region of minimum distortion to suspend it freely from supports with rubber bands. The appropriate positions of the points of suspension are determined from the preliminary simulation of mode shapes from free vibration analysis of the same plate in ABAQUS [25], using nominal values of the material properties. This setup simulates the free boundary condition of the sandwich plate with sufficient accuracy [26]. The frequency of oscillation of the suspended plate is much lower than the frequencies of vibration within the frequency range of interest, thereby justifying the imposed suspension system as somewhat acceptable replication of the free boundary condition. Fig. 1(a) shows the experimental setup for modal testing. Fig. 1(b) shows the schematic diagram of the test including measurement points for excitations and response for a typical sandwich composite plate with a hole. The plates were discretized into grids of 8 × 6 with 50 mm side lengths to get the measurement points. For the acquisition of response as well as the excitation signals, the accelerometer was placed at Point 12 (nodal position in a free vibration simulation of the same plate) and the roving hammer procedure was adopted traversing the entire set of points. Modal tests were repeated for plates with 100 mm, 150 mm and 200 mm diameter central hole.

Modal analysis software ME'scopeVES [27] was used to extract the modal parameters, i.e. the natural frequencies and mode shapes of the sandwich plates. The measured frequencies are presented in serial order of observed modes in Table 1. From the results, it can be observed that central hole/cut-out has significantly shifted the modal frequencies of the sandwich plate from that of the plate with no hole/cut-outs. The presence of central hole of bigger diameter (e.g. 200 mm) has further reduced the frequencies for most of the lower modes as expected. There is no significant change to the mode shapes for the plate with 100 mm or 150 mm diameter holes for the first three modes. However, there
Thereby the similarities and dissimilarities between the experimental mode shapes of the plate with and without holes are judged using the Modal Assurance Criteria (MAC) [28]. A MAC matrix having the diametrical terms approaching unity represents good correlation, whereas MAC values approaching 0 indicate uncorrelated modes. Only the normalized vertical components of the eigenvectors at selected nodes are considered.

Fig. 2 shows superposed plots of mode shapes for plates without hole and plates with 100 diameter concentric holes. The matching of the modes and representation in the superposed diagram has been done based on MAC correlation matrix between the two cases. It can be observed from the figure that first four modes correlate well with the 4th, 5th and the 6th modes switch over amongst themselves for the plate without hole and the plate with 150 mm diameter hole as shown in Fig. 4(b). Similar observations have been made for the MAC correlations between the plate without hole and the plate with 200 mm diameter hole. It is noted that the 4th mode of the plate without hole is correlating well with the 6th mode of the plate having 200 mm diameter hole. Similarly the 6th mode of the plate without hole is correlating well with the 7th mode of the plate having 200 mm diameter hole as shown in Fig. 3(a). This type of mode switchover happens due to the relative directional changes in a plate, for example, after incorporating holes the direction of the plate in which the plate was stiffer may become relatively flexible and therefore from energy consideration, it will be easier for the plate to deform into that direction first. The natural frequency is basically the ratio of changes in the potential energy (hence stiffness) and kinetic energy (hence mass); thereby the diameter and location of the hole determines the relative loss or gain of potential and kinetic energy whose ratio determines the changes in natural frequency.

3. Representative finite element modeling of sandwich composite plates

In the present investigation, an 8 noded three dimensional solid brick elements (C3D8R) have been used to model the sandwich plate in ABAQUS. Perfect bond has been used between the face sheets and the core using tie constraints assuming no existence of interlaminar delamination between the face sheets and the core. The dimension of the sample plate is taken as 300 mm x 400 mm with 30 mm thick core and 2.5 mm face sheet on either sides (Fig. 4(a)) and a typical finite element mesh division for modeling the plate with 100 mm diameter hole as shown in Fig. 4(b). Similar models have been developed for plate with concentric holes of diameter 150 mm and 200 mm but have not been shown here.

![Figure 1](image1.png)

**Fig. 1.** (a) Modal testing of a sandwich composite plate with cut-out, (b) schematic diagram of sandwich plate with 100 mm diameter hole.

### Table 1

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Plate without hole (Hz)</th>
<th>Plate with 100 diameter central hole (Hz)</th>
<th>Plate with 150 diameter central hole (Hz)</th>
<th>Plate with 200 diameter central hole (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>429.56</td>
<td>382.55</td>
<td>334.07</td>
<td>266.81</td>
</tr>
<tr>
<td>2</td>
<td>637.72</td>
<td>600.75</td>
<td>560.94</td>
<td>503.465</td>
</tr>
<tr>
<td>3</td>
<td>849.45</td>
<td>808.66</td>
<td>773.95</td>
<td>726.378</td>
</tr>
<tr>
<td>4</td>
<td>928.17</td>
<td>926.79</td>
<td>892.13</td>
<td>865.683</td>
</tr>
<tr>
<td>5</td>
<td>1024.90</td>
<td>946.20</td>
<td>936.84</td>
<td>942.51</td>
</tr>
<tr>
<td>6</td>
<td>1101.10</td>
<td>1023.0</td>
<td>996.28</td>
<td>1087.67</td>
</tr>
<tr>
<td>7</td>
<td>1254.31</td>
<td>1233.5</td>
<td>1174.7</td>
<td>1317.81</td>
</tr>
<tr>
<td>8</td>
<td>1498.53</td>
<td>1337.9</td>
<td>1340.67</td>
<td>1337.72</td>
</tr>
</tbody>
</table>

are considerable variations in mode shapes for higher modes. It should be noted that since Table 1 lists the modes in a serial order it is difficult to comment on mode-switchover issues (i.e. the interchange of mode serial numbers due to relative changes in elastic moduli in orthogonal directions of the plate).

The MAC correlation matrix has been presented in Fig. 3. The two horizontal axes (in Fig. 3) indicate the modes for sandwich plates with and without hole. The vertical axis indicates the MAC correlations at corresponding modes. The other off-diagonal values do not correlate well as is obvious from the diagram. A value of 60% MAC correlation has been arbitrarily fixed as an acceptance criterion for good correlation in between modes.

The corresponding MAC correlations for plate without hole and the plate with 150 mm hole have been plotted in Fig. 3(a). It can be observed that the 4th, 5th and the 6th modes switch over amongst themselves for the plate without hole and the plate with 150 mm diameter hole.

Similar observations have been made for the MAC correlations between the plate without hole and the plate with 200 mm diameter hole. It is noted that the 4th mode of the plate without hole is correlating well with the 6th mode of the plate having 200 mm diameter hole. Similarly the 6th mode of the plate without hole is correlating well with the 7th mode of the plate having 200 mm diameter hole as shown in Fig. 3(b). This type of mode switchover happens due to the relative directional changes in a plate, for example, after incorporating holes the direction of the plate in which the plate was stiffer may become relatively flexible and therefore from energy consideration, it will be easier for the plate to deform into that direction first. The natural frequency is basically the ratio of changes in the potential energy (hence stiffness) and kinetic energy (hence mass); thereby the diameter and location of the hole determines the relative loss or gain of potential and kinetic energy whose ratio determines the changes in natural frequency.

### Table 1

Experimentally measured frequencies of the FRP plate under free boundary condition.

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>429.56</td>
</tr>
<tr>
<td>2</td>
<td>637.72</td>
</tr>
<tr>
<td>3</td>
<td>849.45</td>
</tr>
<tr>
<td>4</td>
<td>928.17</td>
</tr>
<tr>
<td>5</td>
<td>1024.90</td>
</tr>
<tr>
<td>6</td>
<td>1101.10</td>
</tr>
<tr>
<td>7</td>
<td>1254.31</td>
</tr>
<tr>
<td>8</td>
<td>1498.53</td>
</tr>
</tbody>
</table>
Convergence studies have been performed with reduced mesh sizes to find out suitable discretization for determining the frequencies and mode shapes of the sandwich plates. The final selected mesh sizes are 5 mm on all sides for the core and 10 mm for the face sheets. Only free boundary condition has been explored. A shifted block Lanczos algorithm has been utilized to obtain the eigenvalues and eigenvectors.

It should be noted that the values of the in-plane Young's moduli (i.e. \( E_x \) and \( E_y \)) and the shear moduli (\( G_{xy}, G_{yz}, G_{xz} \)) are estimated through a model updating exercise by correlating the experimentally observed frequencies and mode shapes with the results obtained from an initial finite element model. The densities of the core as well as of the face-sheets are determined experimentally and the Poisson's ratios (isotropic value for the core and in-plane Poisson's ratio \( \nu_{xy} \) and out-of-plane Poisson's ratios \( \nu_{xz} \) and \( \nu_{yz} \) for the face sheets) are assumed nominally. It should also be noted that the modes considered for the current investigation is not sensitive to the value of Young's modulus of the face sheet in thickness direction, i.e. \( E_z \) (which is taken to be considerably smaller than \( E_x \) or \( E_y \)). For the core region, since it is assumed to...
be an isotropic material, the value of Young’s modulus has been taken to be same in all directions.

For the present investigation the gradient based Inverse Eigensensitivity Method (IEM) [29] implemented through the software FEMTools [30] has been used to obtain the updated Young’s moduli and shear moduli. The elastic material values thus obtained are shown in Table 2. These values are assumed to be constants for further numerical investigations.

A typical mode shape comparison of the experimental modes and finite element modes with updated material properties of the plate without hole is shown in Fig. 5. The corresponding MAC values are also shown to indicate the degrees of correlation between modes.

Similarly, the MAC values between the experimental and numerical mode shapes for the sandwich plate with concentric holes are computed. The values corresponding to 100 mm diameter hole and 150 mm diameter hole are presented in Fig. 6. It can readily be observed that the modes correlate quite well. Thereby a representative numerical model has been established.

4. Numerical experimentation

An extensive numerical experimentation has been carried out using the representative finite element model established in the previous section. The objective of this numerical experimentation is to understand the relationship between different variables sensitive to the dynamic behavior of sandwich composite plates. Parameters of interest are thickness of the core, thickness of the face sheets, as well as the diameter and positions of the circular holes or cut-outs and the aspect ratio of the plate. Initially, one or two of the parameters are varied, keeping the others constant.

Table 2
Material property of sandwich composite plate.

<table>
<thead>
<tr>
<th>Material parameter</th>
<th>Core</th>
<th>Face-sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>1.19 N/m²</td>
<td>–</td>
</tr>
<tr>
<td>Density (ρ)</td>
<td>100 kg/m³</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td>Poisson ratio (υ)</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Eₙ</td>
<td>–</td>
<td>1.446E10 N/m²</td>
</tr>
<tr>
<td>Eᵣ</td>
<td>–</td>
<td>1.535E10 N/m²</td>
</tr>
<tr>
<td>Eₜ</td>
<td>–</td>
<td>6E7 N/m²</td>
</tr>
<tr>
<td>Gₓᵧ</td>
<td>–</td>
<td>3.27E9 N/m²</td>
</tr>
<tr>
<td>Gₓₑ</td>
<td>–</td>
<td>5.47E6 N/m³</td>
</tr>
<tr>
<td>Gᵧₑ</td>
<td>–</td>
<td>4.831E6 N/m²</td>
</tr>
<tr>
<td>tₓᵧ</td>
<td>–</td>
<td>0.32</td>
</tr>
<tr>
<td>tₓₑ = tᵧₑ</td>
<td>–</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Fig. 4. (a) Schematic diagram of the sandwich plate (b) finite element discretization of the plate with a hole.

Fig. 5. Comparison experimental and finite element mode shapes.
to understand the nature of variations in dynamic responses, indicated by the changes in natural frequencies.

4.1. Variation of frequencies with core thickness

The core thickness was taken as 30 mm for the experimental case studies. In this numerical investigation, the lower and the upper limits of the core thickness have been chosen as 15 mm (half the experimental core thickness) and 60 mm (twice the experimental core thickness). The results for plate without hole and for the plates with various concentric holes such as 100 mm, 150 mm, 200 mm have been plotted in Fig. 7.

It can be observed from Fig. 7(a) that the frequencies increase monotonically at all modes with increasing core thickness for the plate without hole. Similar observations could be made for lower modes in plates with different concentric holes (refer Fig. 7(b)–(d)). However, this type of pattern could not be observed for higher modes for plates with holes. The result for this deviation in pattern
can be attributed to drastic relative reduction in stiffness due to hole as compared to reduction in mass for certain modes at certain core thicknesses. Thereby from this observation it may be entirely possible to increase the frequency of a sandwich plate with hole especially for higher modes. It is necessary to perform detailed dynamic analysis prior to fix design criteria for sandwich plates with holes.

4.2. Variation of frequency with respect to face-sheet thickness

In these sets of simulations, the variation of natural frequencies of the sandwich plates with respect to the changes in face-sheet thicknesses on both faces are investigated, keeping the core thickness constant (i.e. 30 mm). The thickness of the face sheets is varied from 1.25 mm to 5 mm (half and twice of the face sheet thickness of the experimental sandwich plate respectively). The variations of frequencies are found to be mostly monotonically decreasing for the plate without a hole (Fig. 8(a)). Similar observations could be made for almost all modes in plates with different concentric holes (refer Fig. 8(b)–(d)) with the exception of 7th and 8th mode for plate with 200 mm hole. The result for this deviation in the pattern can be attributed to relative increase in stiffness due to hole as compared to increase in mass for certain modes at certain face-sheet thicknesses. This observation once again supports a thorough dynamic analysis prior to taking any design decisions.

4.3. Variation of frequencies with combined changes in core and face-sheet thicknesses

If an operating frequency range is provided for the sandwich plate, then it is necessary to determine whether introduction of a hole would change the dynamic response of the plate significantly. There may be various combinations of core and face sheet thicknesses which can satisfy the requirements of a particular frequency band. It may not always be effective to increase the frequency of the plate by increasing the core thickness or by reducing the face sheet thicknesses. Thereby it is necessary to observe the combined effect of both the core and face-sheet thickness on the dynamic responses of sandwich composite plates with holes. In order to obtain an insight about the variation in dynamic responses from the numerical experimentation, only two lower modes (fundamental and 2nd mode corresponding to torsional and flexural responses respectively) and two higher modes (6th and 7th corresponding primarily to torsional and bending responses respectively) are presented in Fig. 9. The effects of the other modes have not been presented due to space restrictions. The legend in these figures indicates the diameter of the hole first, followed by the face sheet thickness, e.g. “Hole 100 face 1.25” means the plate is having a concentric hole of 100 mm diameter with face sheet thickness 1.25 mm on both sides.

For the fundamental mode (as observed in Fig. 9(a)) there appears to be a monotonic increase in the variation of frequencies with increasing core thickness and corresponding decrease in face-sheet thickness. However, for the 2nd mode (Fig. 9(b)), as the diameter of the hole increases, there is a non-uniform variation of the frequencies for certain core and face-sheet thickness combination. For example, with 5 mm face sheet thickness the frequency of the 2nd mode almost remains same even after increase of the core thickness from 40 to 50 mm for sandwich plate with 200 mm hole. Moreover, the frequency dips down for 5 mm face sheet thickness with 150 mm hole compared to the 200 mm hole as the core thickness is increased from 50 to 60 mm. Similar trends...
of non-uniform variations could be observed at higher modes in Fig. 9(c) and (d). This apparently weird behavior of overall loss of stiffness of the sandwich plate with bigger diameter holes could not be compensated enough by increasing the core thickness. Hence the global natural frequency of the plate reduces despite the fact that there is an increase in core thickness. Similarly, there may not be any increase in stiffness even after decrease of face sheet thickness for larger diameter of the holes.

The curves thus prepared can also be used to determine readily a particular set of parameters against a desired frequency range of interest. For example, if it is known that the frequencies of operation of a sandwich plate needs to be confined between 300 and 400 Hz, ranges of appropriate values of face sheet thicknesses can be selected for a chosen value of core thickness in the design so that the 1st fundamental frequency falls within this range. Similarly, appropriate values of core thickness can be selected for a chosen face sheet thickness and a frequency band. Similar investigations can be carried out for higher modes as well.

The same set of curves can also be utilized to decide about the limiting values of frequencies that may be affected by the choice of a particular set of values of core and face sheet thicknesses with certain pre-decided diameter of hole.

4.4. Variation of frequencies with respect to changes in the position of hole

Variations of frequencies can be represented graphically by sets of curves drawn for various locations of the hole. Fig. 10 shows one such set of frequency variations for 100 mm central diameter of the hole, with core thickness 30 mm and face sheet thickness 2.5 mm. The hole maintains a minimum distance of 50 mm from the edge. Case 1 depicts the variation of frequencies with a concentric hole;
whereas Case 2, Case 3 and Case 4 represents the frequency variations for plate with holes eccentric along the longitudinal axis, transverse axis and diagonal axis respectively, maintaining the prescribed minimum distance of 50 mm from the nearest edge.

From Fig. 10 it can be observed that the variations in frequencies are not substantial for lower modes but are considerable at certain higher modes for different positions of holes. Significant increase in frequency is observed at the 6th mode for Case 2 and 3. This may be explained in conjunction with the 6th mode shapes of the plate with 100 mm concentric hole (Fig. 2). The shifting of the hole from the centre towards the direction of smaller radius of curvature of the plate will result in more incremental changes to the frequencies. From the figure it is clear that the most effective average reduction considering all frequencies can be achieved in Case 2 i.e. plate with holes eccentric along the longitudinal axis.

4.5. Variation of frequencies with respect to diameter of hole located along the diagonal

Investigations have been carried out to determine the relationship of variation of frequencies with core thickness for various face sheet thicknesses and hole diameters, when the hole is placed eccentrically as explained in Fig. 11. It may be noted that the prescribed minimum distance of the hole is maintained at 50 mm from any side of the plate. It is interesting to note that the variation of frequencies at higher modes will have many non-uniform variations as shown in Fig. 12.

Distribution of stiffness within the plate becomes further lop-sided as the diameter of the eccentric hole (along the diagonal) is increased, keeping minimum prescribed distance from the sides. Frequencies of the plate vary widely for different combinations of core and face sheet thicknesses and may have intersections in the

![Fig. 11. Locations of eccentric hole having different diameters in the sandwich plate.](image)

Fig. 12. Frequency variation of modes for different combination of core and face sheet thickness and diameter of hole located at corner keeping minimum 50 mm distance from edge for (a) 1st mode (b) 2nd mode (c) 6th mode (d) 7th mode.
curves, as is apparent for some of the higher modes as shown in Fig. 12. For example, in the case of 200 mm eccentric hole, the frequency of the 6th mode of the plate with 1.25 mm face sheet decreases whereas the frequency increases for 2.5 mm face sheet. The core thickness has the same incremental increase from 30 to 40 mm in both cases. The increase in frequency due to reduction of face-sheet thickness is counterbalanced by the corresponding increase due to loss of stiffness with increase in diameter of hole.

4.6. Variation of frequencies with plate aspect ratio

The investigations so far have been restricted to a sandwich plate of size 400 mm × 300 mm. This aspect ratio has been preliminary selected so as to avoid closely spaced and/or repeated modes which may occur in square plates or plates having aspect ratio exactly of multiples of integers. The effects of aspect ratio of the plate on the frequencies have now been extended further to include a few more rectangular configurations, yet maintaining aspect ratios which result into mostly well separated modes. Rectangular plates of dimensions 300 mm × 200 mm and 500 mm × 300 mm are investigated to observe if there exists any difference in the observed dynamic characteristics of the sandwich plate with holes. The results of the variations of the fundamental frequency for the plate without hole and with concentric hole of diameter 100 mm for different plate aspect ratios are presented in Fig. 13. Other results are not presented for brevity.

Here, 3 × 2_1.25 means the size of the plate is 300 mm × 200 mm and the face sheet thickness is 1.25 mm on both sides, whereas the core thickness is kept constant (30 mm).

It may be observed from Fig. 13 that the trends of the curves showing variations of frequencies have not changed as the aspect ratio of the plate is altered. This may be explained from the fact that the basic dynamic characteristics, i.e. the pattern of the mode shapes, have not changed significantly for the present investigations related to the rectangular plate for the chosen ranges of aspect ratios.

5. Discussions

An exhaustive mixed experimental–numerical study has been presented investigating as to how the dynamic performance of a sandwich composite plate is affected by the introduction of holes. The study also provides guidelines on what combinations of design parameters, such as the core thickness, face-sheet thickness, diameter of hole and its position are desirable to keep the dynamic performance (such as, the natural frequencies of the sandwich plate) within desired values. In case, some sophisticated instruments are to be mounted or structural modifications are sought in terms of proposed service holes at designated locations. The changes in frequencies at various modes can only be predicted by conducting such rigorous studies. The investigation of changes in frequencies with respect to core thickness and face sheet thicknesses for plate with a hole, indicates that for higher modes, the frequencies may not increase with increase of core thickness or with decrease of face sheet thickness. This indicates a possibility of an optimum diameter of hole beyond which, increase in core thickness may not be an effective measure to increase the frequency of the plate, especially for higher modes. Same is applicable for the face sheet thicknesses: the higher modal frequencies cannot be increased by decreasing the face sheet thicknesses beyond certain core thickness. The study demonstrates that the frequency reduces towards the minimum as the hole moves off-centre towards the larger side of the plate. It has been observed that the particular modes which are affected the most for different plates will be dependent upon the combined effects of core thickness, face-sheet thicknesses and the aspect ratio of the plate, as well as diameter and location of the hole. A thorough dynamic investigation is always necessary for further modification of the design of the sandwich plate for required dynamic performance.

6. Conclusions

Investigations have been carried out for sandwich plates with holes at various locations to determine the effects of core thickness, face sheet thicknesses, diameter of the hole and aspect ratio of the sandwich plate on the changes in frequencies of various modes. It has been observed that all the above mentioned parameters are contributing to the changes in dynamic responses and a detailed analysis can only ascertain the correct combination of the parameters for achieving a desired dynamic performance of such sandwich plates. The variation of frequencies may not be always monotonic for higher modes for sandwich plate with holes. The study is limited to rectangular sandwich plates with circular through holes only. Free boundary condition has been only explored in this study.
References

[27] VES ME. Ver. 4.0.0.96. Vibrant Technology Inc.; 2007.