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Vibration Analysis of a multi core sandwich composite beam with cutouts—A critical investigation

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Abstract

The prime objective of this research work is focused on assessing the dynamic characteristics of a multi core sandwich composite beam with cutouts. The effect of introducing additional cores in sandwich beams is investigated in detail along with various geometric configurations. Also, the impact of placing multiple cutouts with assorted geometric profiles (Circular, Square, Hexagon and Triangular) in a sandwich structure is also addressed in detail. Finite element technique is deployed for numerical analysis and parametric studies. In addition, the influence of reinforcements in the proposed structure is also presented. From the results, it is evident that square cutouts possess the highest damping capability irrespective of geometric position of its placement. Also, it may be concluded that the geometric position of placing cutouts significantly influences the magnitude of frequency levels ranging to maximum of 42% hike at lower modes. Moreover, introduction of cutouts leads to reduction in frequency levels for all the cases up to 20%. Furthermore, secondary investigation of multicore reinforced sandwich beams experiences a maximum reduction in frequency of about 15%.

1. Introduction

Sandwich layers are now widely used in various industrial applications, which are usually characterized by dual thin face sheets with a thick, soft core. This kind of structures has now widely been applied in civil constructions, mechanical structures, aerospace applications, marine engineering, and lightweight materials. The face sheets of the sandwich structure are carefully selected to exhibit higher rate of stiffness and strength, whilst the center core area is made of foam like soft materials with a purview for energy absorption and weight reduction. Sandwich structures are preferred to maximum extent owing to its high strength to weight ratio and high stiffness to weight ratio. All structural models are designed in a fashion to exclude resonant frequency in any working condition to avoid failure of the entire mechanisms and allied components. Introduction of cut-outs in engineering structures are almost inevitable. Also, most the machine components are subjected to fatigue and dynamic loading conditions. Hence, assessment of the dynamic characteristics of such machine components is a vital task in design and development of the product. Moreover, exact prediction of such factors helps the industry to be operated at low-risk profiles.

Plass [1] suggested the use of sandwich plates for guided missiles to keep the amplitude of vibrations at lower levels for smooth flying. Numerical investigations are carried out to assess the vibration characteristics of visco-elastic sandwich beams with different boundary conditions [2]. The behavior characteristics of shell and sandwich structured objects are further documented in the works of Teichmann et al [3], Goodies and Hsu [4] and Vinson [5]. A full set of numerical prediction models for important boundary conditions were developed by Rao [6] and illustrated clearly using various examples. Daniel and Abot [7] experimentally derived the behavior of flexural composite beams and related the results with theoretical predictions. Further, they concluded that the failure of the composite sandwich beam due to the poor flexural strength of the honeycomb core material. Moreover, the failure modes of the face sheets are also evaluated with the aid of experiments and fringe pattern...
investigations. The major factors are summarized as face sheet compressive failure, face sheet debonding, indentation failure, core failure and face sheet wrinkling [8]. The failure modes and peak loads affecting metallic foam cores are presented by McCormach et al [9] and the numerical results are validated with the experimental assessment.

Fanglang et al [10] carried out analysis to reveal the effects of cut out on sandwich composite fiber beam over its respective natural frequency and mode shape. The dynamic behavior of sandwich beams with HEREX core is studied and finite element model using ANSYS is used to calculate natural frequencies and mode shape on the sandwich beams [11]. The frequency variation of cut out of laminated composite beam on natural frequency, also the impact of cut out position is investigated [12]. A sandwich beam theory is used to investigate the natural frequency of composite core sandwich beams. The analytical solution for the natural frequency and mode shape of cut outs on sandwich beams are presented [13]. The vibration performance of sandwich beams with composite core was investigated in this research. FEM and modal analysis techniques have been used to find out the natural frequency characteristics. It was found that the natural frequency varies with reference to the cut out on the beams [14]. Nayak et al [15] used Reddy’s higher order computation theory to assess the vibration behavior of sandwich beams. The buckling analysis of sandwich structures are estimated by Karamanli and Aydogdu [16] and the same concept was extended by Kumar and Srinivasa [17] for cylindrical shells. The layer-wise variability of material properties and position-wise variability of cut outs also geometries-wise cut outs are investigated [18]. Buckling analysis of de-bonded sandwich systems were analyzed using FEM and Ritz technique and it was concluded that the results provided by the later method was superior in all aspects [19, 20]. Hung and Truong [21] studied the free vibration characteristics of sandwich beams with functionally graded material layers and a porous core. Also, a wide range of parametric analysis was also performed. A novel zig-zag beam theory is developed for the free vibration problem of soft-core sandwich beam. The results of this prove that this theory is more suitable for solving this kind of problems and the results matches with all popular theories [13].

Recently, Eltaher and Mohamed [22] presented a complete model to describe the buckling stability and allied mode shapes based on higher order shear deformation equations for a laminated sandwich beam structure. Differential quadrature method is deployed for numerical evaluation and the predictions are also compared with other prevailing mathematical concepts. The dynamic modelling effects of multi-layered lattice structured sandwich beams are studied with the aid of finite element technique and further verified by experiments [23]. Rahmani et al assessed the vibration behaviour of sandwich beams with functionally graded face sheets based on Hamiltonian principle and Galerkins method. The equation formulations are reduced with the aid of algebraic techniques [24]. An effective and simple method was developed by Liu et al [25] to predict the vibration and buckling pattern of multi-span lattice composite sandwich beams. Parametric investigation and the effect of span length were thoroughly investigated. Further, an interesting investigation was reported by Zang et al [26] which focused on assessing the dominant factors that affect the free vibration characteristics of carbon-fiber reinforced plastic (CFRP) laminate with cutouts. Civalek and Kiracioglu [27] utilized the discrete convolution singular method (DSCM) for deriving a numerical solution to study the vibration characteristics of Timoshenko beam. The presented results are also compared with other solutions available in literature and a good agreement is endorsed. Further, the same theory of DSCM was extended to analyse the free vibration response of functionally graded cylindrical shells. Stainless steel, zirconia and nickel materials were used in the analysis [28]. Recently, Sahu and Das [29] developed an exclusive MATLAB code based on finite element method to analyses the vibration behavior of composite beams with cracks. A complete review of literature clearly suggests that utilization of finite element theory gives high accurate results with lesser computation time for complex structures.

Although numerous research works were carried out on sandwich structures, negligible quantum of works has only been reported in assessing the dynamic characteristics of multi-core composite sandwich beam structures. Moreover, critical investigation pertaining to introduction of cutouts in a sandwich beam system are also very limited. Hence, in this research work, an attempt has been made to investigate the effects of placing various types of cutouts in a composite sandwich beam, influence of multi-core layouts and its vibration characteristics are studied in detail.

2. Geometric modelling and finite element analysis

Figure 1 depicts the basic geometric structure of the proposed sandwich beam with dimensions. The beam is divided into three layers (facing and core) of different material properties. The analysis is clustered into two cases. The first case (case I) represents the sandwich beam analyses with cutouts and the later one (case II) exhibits the layout of multi-cored structure. The length and width of the beams are considered as 150 mm and 20 mm respectively and the data is kept constant throughout the study. The thickness of both the face sheets are
also kept constant with a magnitude of 1.6 mm. For parametric investigation, the height of the soft-core layer is varied from 1.2 mm to 2 mm in steps of 0.2 mm resulting in five different configurations. Moreover, cutouts with square, circle, triangle and hexagon profiles are placed at various geometric locations in the beam as depicted in figure 2. Initially the cutouts are place exactly at the center of beam and then multiple cutouts (three and four) are placed at equidistant spots along the length of the proposed sandwich beam structure. Figure 3 exhibits the novel multi-core formation (case II) with nineteen distinct profiles with various material and geometric combinations. Length wise gaps and width wise gaps are placed in case ID ranging from A to I. The proportion of soft-core layer mix is varied in five different length ratios. Case ID J to M represents dual-core beams with the same length mix ratio. Finally, the case ID O to S portrays the formulation of a single
reinforcement model covered box shaped face structures with varying widths ranging from 2 to 16 mm. Moreover, the material properties for both the cases used in this research work are portrayed in Table 1 for clarity.

ANSYS™ commercial FEM software is used for solving the entire analysis and critical assessment. The sandwich beam is modeled and meshed using SOLID 186 [3] element. This element is a higher order quadratic 3D element, having 20 nodes and 3 degrees of freedom per node. Also, it supports curved geometry and multi-layered structures. The layers of beam (face sheets and soft-core) are modeled separately in three dimensions and glued together to enable smooth load transformation. Delamination of the face sheets are not considered in this study and it is assumed that all these layers are bonded strongly. The sandwich model is meshed with both hexahedral and tetrahedral structures and a sample exhibit is shown in Figure 4 for clarity. The Eigen values natural frequencies and its corresponding mode shapes for ten modes are extracted using Block Lanczos solver.

![Figure 3. Geometric structure of proposed multi core sandwich beam (Case II).](image-url)

### Table 1. Material properties of the sandwich beam.

| Facing [17] | $E_1 = 172.5$ GPa, $E_2 = 6.9$ GPa, $E_3 = 6.9$ GPa, $G_{12} = G_{13} = 0.5$ GPa, $G_{23} = 1.38$ GPa, $\nu_{12} = \nu_{13} = \nu_{23} = 0.25$, $\rho = 1600$ kg m$^{-3}$ |
|--------------|--------------------------------------------------|
| Core layer 1 [30] | $E_1 = E_2 = E_3 = 0.10363$ GPa, $G_{12} = G_{13} = 0.05$ GPa, $\nu_1 = \nu_2 = \nu_3 = 0.33$, $\rho = 130$ kg m$^{-3}$ |
| Core layer 2 [30] | $E_1 = 0.529$ GPa, $E_2 = 0.0449$ GPa, $E_3 = 1.3$ GPa, $G_{12} = 0.0237$ GPa, $G_{13} = 0.318$ GPa, $G_{23} = 0.129$ GPa, $\nu_{12} = \nu_{13} = \nu_{23} = 0.291$, $\rho = 149$ kg m$^{-3}$ |

$E_x$—Young’s Modulus, $G_{xy}$—Shear Modulus, $\nu_{xy}$—Poisson’s ratio and $\rho$—Density
3. Results and discussion

3.1. Influence of core thickness (case I)
For all thirteen configurations as represented in figure 2, the first ten modes are considered for discussion. The thickness of the core is varied from 1.2 mm to 2 mm in steps of 0.2 mm. Macro level assessment reveals that, there is no significant variation in the magnitudes of natural frequency (figure 5). Further, on micro level investigation, it may be noted that there is an increase in frequency levels as the thickness of core layer is increased and hence it may be concluded that the magnitude of natural is directly proportional to the thickness of soft-core layer. The same fashion is repeated for all the modes.

3.2. Effect of varying the cut-outs position and multi-cutouts (case I)
The location of center points of single cutouts (circle, triangle, hexagon and square) is placed at 30, 45, 60, 75, 90, 105, 120 and 135 mm respectively from the fixed end of the cantilever sandwich beam. This is a critical study to assess the impact of selecting the geometric position of placing cutouts that may be idle for certain industrial applications. To perform a relative analysis, the ratio of placing the cutouts at extreme end 135 to the nearest...
point of 30 mm from the fixed position is considered and the plot (figure 6) is drafted for further discussion for all the ten modes. From close observation, it may be noted that the position of the cutout along the length of the beam plays a significant role in determining the resulting amplitudes of frequency levels. At lower modes, a maximum hike of about 42% is evidenced and lower variation can be seen at higher modes. Modes 5 and 8 does not show any variation for all the profiles. Moreover, the profile of the cutout has also considerable effect at lower modes.

Figure 8 portrays the overall comparison of the cantilever sandwich beam comprised of various cutout profiles. The numerical values shown in figure 7 represent the corresponding frequency values for respective modes. From the results, it may be concluded that square shaped cutouts possess the highest damping capability for all the combinations. The reduction in natural frequency is achieved because of the change in apparent stiffness of beam which the directly related the available cross-sectional area. To have a better clarity, a detailed analysis is displayed in figure 8 which explains the relationship between frequency levels and cutouts for the first mode.

3.3. Discussion on multi-core sandwich beams (case II)

Figure 9 exhibits the variation of natural frequency for multi-cored structures. From the exhibit, From the graph, it may be noted that the magnitude of natural frequency varies inversely with the increase in dimension of gap placed in cores. Also, introduction of gap in core layer reduces the frequency significantly from 320 Hz to 271 Hz.
Lengthwise placement of gaps is preferable for enabling maximum damping characteristics. In addition to the previous case, now the gaps are replaced by new core material resulting in a dual core sandwich structure. The lengthwise divisions are varied from 5 to 13. Introduction of dual core increases the natural frequency and there is less significant variations in each mode for all the five divisions. The last four cases replace the dual cores by a single reinforced core. The width of the reinforcement is varied from 2 mm to 16 mm in steps of 4 mm. Maximum frequency occurs at 6 mm to 12 mm reinforcement thickness and thereby it gets reduced on both the extremities and finally saturates with the values of full core characteristics. Also, figure 10 is plotted to reveal the variation in the amplitudes of natural frequencies for mode 1 to have a better insight. Sandwich beams having air gaps positioned along the length of the beam possess the highest damping characteristics followed by widthwise positions and multicore layouts. Single reinforcement models are not preferred as the structure amplifies the frequency to the maximum extent.

4. Summary and conclusion

This research work presents the significant results of introducing cut-outs in a sandwich composite beam. Also, the effects of introducing multiple cores are discussed in detail. Based on the assessment, the following conclusions are drawn:

- The thickness of soft-core layer has negligible significance over the amplitudes of frequency values.
- Upon introducing cut-outs, drastic reduction in frequency can be achieved up to 22%.
- Square cut-out’s possess highest damping capability.
The order of priority in selecting the cut-out shapes are square, circle, hexagon and triangle.

The geometric location of placing a single cut-out has predominant effect on the natural frequency.

Maximum damping capability is in the case of gaped cores with lesser divisions. Moreover, Lengthwise gaps are preferable than provably widthwise gaps.

Sandwich beams fabricated with single reinforced soft cores amplifies the magnitude of natural frequency about 10%. Also, if the width of the core reinforcement is minimum, the value of natural frequency is maximum.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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