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Effect Of Sinusoidal and Inverse Sinusoidal Load on The Vibration and Buckling Behaviour of Laminated Composite Symmetrical and Unsymmetrical Trapezoidal Panels

Maharudra[1,*], Thara L[2], Subash Chandra K S[3], Shiva kumara N V[4], Santhosh Gotagunaki[5], Manjunatha K[6]

Abstract

Using finite element (FE) techniques, this work analyzes the influence of sinusoidal and inverse sinusoidal stresses on the buckling behavior of trapezoidal laminated composite panels (also known as trapezoidal laminated composite panels). The discretization of the composite panel is accomplished by the use of an eight-noded iso-parametric plate element, which has five degrees of freedom for each node. Due to the incorporation of Higher Order Shear Deformation Theory (HOSDT) into the mathematical formulation, the model is able to adequately account for shear deformation. This allows the model to be acceptable for both thin and thick panels without the need for extra shear correction variables. The validity of the model is validated by comparing the findings generated by the model with those obtained from previously published research. Ply orientations, panel geometry, and panel cutout sizes are some of the factors that are included in the parametric studies that are carried out in order to investigate the impact of these characteristics. The findings of this study contribute to a better knowledge of the vibration and buckling behavior of trapezoidal laminated composite panels across a wide range of loading situations and parameter modifications. With the use of HOSDT, reliable predictions are guaranteed, especially in situations that include both thin and thick panels. This provides significant insights that can be used to optimize the design and performance of composite structures in actual engineering applications.

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INTRODUCTION TO LAMINATED COMPOSITE STRUCTURES

Laminated composite materials have gained significant popularity in various engineering applications due to their superior strength-to-weight ratio, high stiffness, and corrosion resistance. These composites are widely used in aerospace, marine, and automotive industries where performance under mechanical and environmental loads is critical. Composite laminates are typically made by stacking layers of fiber-reinforced materials, with fibers oriented in different directions, allowing the material properties to be tailored to specific design requirements. Various studies have investigated composite panels, including trapezoidal and perforated shapes, for their buckling and vibration characteristics under diverse loading conditions [1,2,3,4].

Higher-Order Shear Deformation Theory (HOSDT) in Laminates

The Higher-Order Shear Deformation Theory (HOSDT) has proven to be an essential tool for analyzing laminated composite structures, especially when shear deformation plays a significant role. HOSDT accounts for transverse shear deformation without requiring shear correction factors, making it suitable for both thin and thick laminates. This theory has been applied in several studies to predict the stability and dynamic behavior of composite structures accurately. Reddy and Phan [5] utilized HOSDT for stability and vibration analysis of laminated plates, while Biswas et al. [6] employed a refined higher-order zigzag theory for hybrid laminate analysis. Belkacem et al. [7] also explored the application of higher-order theories in buckling and free vibration analysis, reinforcing their relevance for complex composite structures. Bui et al. [8] introduces a comprehensive higher-order shear deformation theory for the accurate buckling and free vibration analysis of laminated thin-walled composite, significantly enhancing the precision of structural performance predictions.

Studies on In-Plane Loads and Buckling Behavior

The impact of in-plane loads on the buckling and vibration behavior of laminated composite panels has been a focal point of research. Chandra et al. [9] explored the effects of sinusoidal and inverse sinusoidal in-plane loads on FRP panels with cutouts, while Chandra et al. [10] examined the influence of hygro-thermo-mechanical loads on vibration and buckling of composite laminates. Studies like these highlight the critical role of varying in-plane and concentrated loads in determining the stability and vibrational characteristics of composite panels under practical conditions [11,12].

Trapezoidal Laminated Composite Plates

The unique geometrical configuration of trapezoidal laminated composite plates makes them suitable for specific structural applications, prompting numerous studies on their buckling and vibration behavior. Maharudra et al. [13] investigated the thermal buckling behavior of trapezoidal perforated composite plates, while Arya and Rajanna [14] focused on the vibration characteristics of trapezoidal laminated composite plates with and without cutouts. Further, researchers like An et al. [15] studied the free vibration characteristics of cantilevered sandwich trapezoidal plates with variable thickness, emphasizing the complex behavior of these plates under various conditions. Other contributions include the study of local stiffeners and cutout shapes on stability [16], and the dynamic behavior under thermo-mechanical loading [17,18].

Gaps in the Literature

Despite extensive research on laminated composites, several gaps remain, particularly regarding trapezoidal panels under complex loading conditions. Most studies have focused on uniform loads or simple geometrical configurations, leaving a gap in understanding the behavior of composite panels under non-uniform in-plane loads such as sinusoidal and inverse sinusoidal loads. Furthermore, while HOSDT has been widely applied, more research is needed to validate its accuracy across different boundary conditions and laminate configurations. The combined effects of varying geometries, boundary conditions, and load patterns on both symmetrical and unsymmetrical trapezoidal panels have not been fully explored [19,20,21,22].

Present Study on Trapezoidal Panels

The present study aims to address these gaps by investigating the vibration and buckling behavior of laminated composite symmetrical and unsymmetrical trapezoidal panels under sinusoidal and inverse sinusoidal loads. By employing Higher-Order Shear Deformation Theory (HOSDT) in the finite element model, this research provides a more accurate representation of the panel's behavior under various loading conditions. The study also explores the effects of ply orientations, panel geometry, and cutout sizes on the buckling and vibration performance of these panels, offering valuable insights for optimizing the design and performance of composite structures in practical engineering applications.

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FINITE ELEMENT FORMULATION & GOVERNING EQUATIONS

In Figure 1, a standard laminated plate coordinate system is depicted, providing essential geometric and dimensional details. Figures 1 and 2 illustrate [1] a scenario where a laminated plate, uniform in thickness "z", consists of numerous thin lamina, each arbitrarily oriented at an angle "θ" relative to the reference coordinate system. The Figure 3 illustrate Sinusoidal load with trapezoidal panel [1], Figure 4 illustrate Inverse sinusoidal load with trapezoidal panel [1] and Figure 5 illustrate load distribution diagrams applied in this work are as follows [1,13,21].

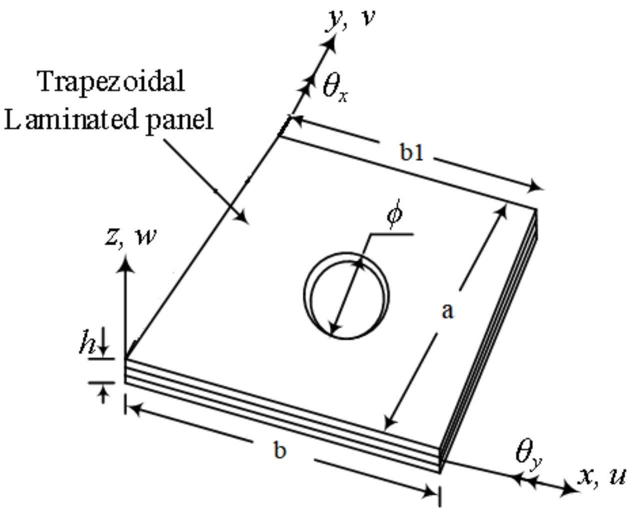


Figure 1. Coordinate system defining the geometry of a laminated plate.

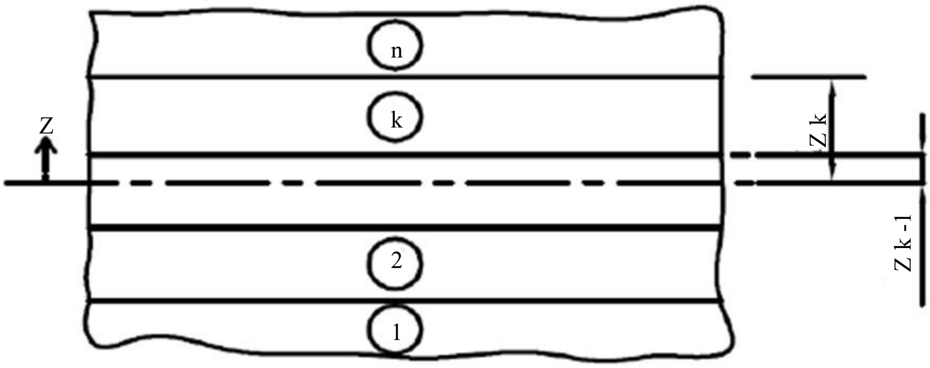


Figure 2. Stacking sequence illustrating the arrangement of individual layers within a composite layered laminate.

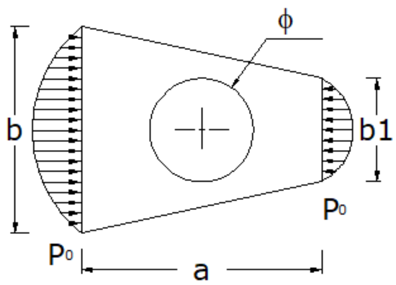


Figure 3. Sinusoidal load with trapezoidal panel.

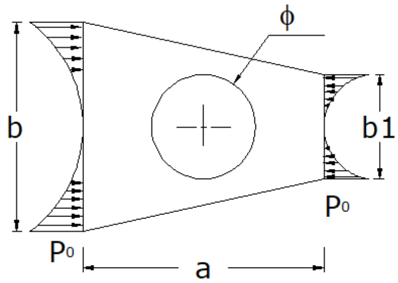
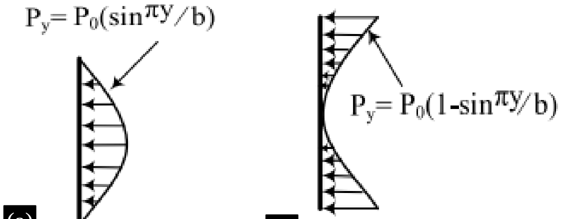


Figure 4. Inverse sinusoidal load with trapezoidal panel



(a) Sinusoidal load (b) Inverse sinusoidal load.

Figure 5. Load distribution diagrams applied in this work [1,13,21].

The theoretical formulation for laminated plates using Higher-Order Shear Deformation Theory (HOSDT) typically involves the following key equations:

Displacement Field

The displacement field for HOSDT accounts for both bending and shear deformations. It is often expressed as a combination of in-plane and out-of-plane displacements:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_s \end{bmatrix} \begin{Bmatrix} a \\ b \\ c \end{Bmatrix}$$

Where:

u, v and *w* are the displacements in the x, y, and z directions respectively.

Nx, *Ny* and *Ns* are the shape functions for in-plane displacement, out-of-plane displacement, and shear deformation, respectively.

a, *b* and *c* are the nodal degrees of freedom.

The displacement field theory postulates that while the mid-plane remains straight following deformation, the normal to this plane may not remain straight

According to HOSDT displacement field can be expressed as,

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\theta_x(x,y) + z^3\theta_x^*(x,y) \\ v(x,y,z) &= v_0(x,y) + z\theta_y(x,y) + z^3\theta_y^*(x,y) \\ w(x,y,z) &= w_0(x,y) \end{aligned} \tag{1}$$

The strain displacement equations for both linear and non-linear strains are formulated using Green-Lagrange's method. Whereas an elastic stiffness matrix is derived from linear stresses, a geometric stiffness matrix is derived from non-linear strains. It is possible to express the constitutive relationship to the laminated plate as

$$\begin{Bmatrix} N_i \\ M_i \\ M_i^* \\ \phi_i \\ \phi_i^* \end{Bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} & C_{ij} & 0 & 0 \\ B_{ij} & D_{ij} & E_{ij} & 0 & 0 \\ C_{ij} & E_{ij} & F_{ij} & 0 & 0 \\ 0 & 0 & 0 & H_{ij} & K_{ij} \\ 0 & 0 & 0 & K_{ij} & M_{ij} \end{bmatrix} \begin{Bmatrix} \varepsilon_j \\ \kappa_j \\ \kappa_j^* \\ \theta_j \\ \theta_j^* \end{Bmatrix} \tag{2}$$

In this expression, Aij, Bij, Cij, Eij, Fij, and Hij represent the usual extension-extension-shear coupling, extension-bending coupling, bending-bending-twisting coupling, and shear coupling terms, respectively. Additionally, Kij and Mij are also included

The total potential energy (U) and kinetic energy (T) can be expressed in matrix form as follows:

$$U = \frac{1}{2}\{d\}^T [K]\{d\} \tag{3}$$

$$T = \frac{1}{2}\{\dot{d}\}^T [K]\{\dot{d}\} \tag{4}$$

The stiffness matrix can be formulated as:

$$[K] = [K_e] - P[K_G] \tag{5}$$

The governing equilibrium equation of motion for the plate subjected to in-plane loading can be formulated as:

$$[M]\{\ddot{d}\} + [K_e]\{d\} - P[K_G]\{d\} = 0 \tag{6}$$

Where [Ke], [KG], and [M] represent the assembled system stiffness, geometric stiffness, and mass matrices, respectively. Here, {d} denotes the eigenvector corresponding to different vibration modes. The governing equation above can be simplified for vibration and buckling analyses as follows:

The final form of Equation (6) can be written as:

$$[K_e]\{d\} - \omega^2 [M]\{d\} = 0 \tag{7}$$

Equation 7 represents a free vibration problem without any in-plane load.

$$[K]\{q\} - P_{cr}[K_G]\{q\} = \{0\} \tag{8}$$

The buckling forces corresponding to different modes are the eigen functions of the aforementioned equation. The minimum buckling force is commonly referred to as the structure's critical load.

COMPUTER PROGRAM

The provided description outlines the computational approach used in the FORTRAN program to analyze laminated composite structures, particularly to address potential shear locking issues and accurately compute stresses and mass properties.

To prevent shear locking, a selective integration strategy is implemented. This involves using different Gauss rules for shear terms (2 x 2 Gauss law) and membrane/bending relations (3 x 3 Gauss rule). This approach allows for more accurate computation of the element's elastic stiffness matrix. To determine stresses at Gauss sampler sites, a plane stress analysis is performed. This accounts for the non-uniform in-plane stress distribution caused by functional loading. This step ensures accurate stress calculations within the element. A 3 x 3 Gauss rule is used to obtain the element mass matrix. This matrix is essential for analyzing the dynamic behavior of the structure, particularly in vibration analysis. Related element-level matrices are assembled to form distinct global matrices. This likely involves combining stiffness and mass matrices while considering boundary conditions and element connectivity. The skyline approach is employed to efficiently store and manipulate large sparse matrices. This method reduces memory requirements and computational overhead, making it suitable for handling the global matrices efficiently. Subspace iteration is used to resolve the eigenvalues of the system. This iterative approach is effective for computing a subset of eigenvalues and corresponding eigenvectors, which are crucial for analyzing the dynamic behavior of the structure. Overall, the described computational approach ensures accurate and efficient analysis of laminated composite structures, considering both static and dynamic behavior while mitigating potential numerical issues such as shear locking.

MODEL VALIDATION

The material characteristics employed in the current study are listed in Tables 1 to help validate the results with the prior research. The laminated plate under consideration has dimensions of a=b=100. It uses symmetric ply-orientations (±θ) and a range of b/h ratios.

The frequencies obtained in the results are presented in non-dimensional form.

Non-dimensional frequency for composite is, $\overline{\omega} = \omega b^2 \sqrt{\rho/(E_y h^2)}$

The results obtained from the FORTRAN program are in good agreement with the formulations by Reddy and Phan (1985) for S-S (simply supported) boundary conditions, as demonstrated in Table 2. The comparison likely includes various parameters such as natural frequencies, mode shapes, or other relevant vibration characteristics. Furthermore, the agreement between the results obtained from the FORTRAN program and the formulations by Reddy and Phan [5] is observed for both two-layered and eight-layered laminated panels. This indicates the accuracy and reliability of the computational approach implemented in the FORTRAN program, as well as its ability to handle different layer configurations of laminated composite panels effectively. Such validation against established formulations from previous literature adds credibility to the FORTRAN program's results and confirms its suitability for analyzing laminated composite structures under S-S boundary conditions. This validation process is crucial for ensuring the accuracy and trustworthiness of numerical simulations and computational analyses in engineering applications.

Table 1. Material properties.

Material	**Material Properties for Model Validation**					
	E_x	E_y	G_{xy}	G_{xz}	G_{yz}	v_{xy}
Composite	40.00	1.00	0.600	0.600	0.500	0.250

Table 2. Comparison of nondimensional natural frequencies of square plates.

b/h	**Ply-Orientation**	**(Reddy and phan 1985)**	**Present results**	
		HSDT	***Mindlin theory***	***HSDT***
		Non-dimensionalised frequency(ω)	***Non-dimensionalised frequency***	***Non-dimensionalised frequency***
5.0	[45^0/-45^0]	10.3351	10.2432	10.6812
10.0	[45^0/-45^0]	13.0442	12.9751	13.2071
20.0	[45^0/-45^0]	14.1791	14.1532	14.2301
100.0	[45^0/-45^0]	14.6181	14.6172	14.6024
5.0	[45^0/-45^0/45^0/-45^0/45^0/-45^0/45^0/-45^0]	12.8922	12.8621	12.9601
10.0	[45^0/-45^0/45^0/-45^0/45^0/-45^0/45^0/-45^0]	19.2892	19.2353	19.2664
20.0	[45^0/-45^0/45^0/-45^0/45^0/-45^0/45^0/-45^0]	23.2591	23.8992	23.2393
100.0	[45^0/-45^0/45^0/-45^0/45^0/-45^0/45^0/-45^0]	25.1761	25.1744	25.1753

Table 3. Nondimensional uniaxial buckling load of simply supported two-layer (θ/−θ) square laminates [1,13,21].

b/h	Theory	Non dimensional buckling load	
		θ = 30◦	***θ = 45◦***
4	Present Model	9.5364	9.8200
	B Adim [12]	9.5554	9.9145
	Reddy [13]	9.3391	8.2377
	FSDT [14]	7.5450	6.7858
10	Present Model	17.1510	18.1558
	B Adim [12]	17.2737	18.1473
	Reddy [13]	17.1269	18.1544
	FSDT [14]	16.6132	17.5522
100	Present Model	20.4993	21.6612
	B Adim [12]	20.5040	21.6662
	Reddy [13]	20.5017	21.6663
	FSDT [14]	20.4944	21.6576

The comparison study of the nondimensional uniaxial buckling load for simply supported two-layer (θ/−θ) square laminates reveals that the results from the Present Model align closely with those from B Adim [7] and Reddy [23] across different b/h ratios and fiber orientations (θ = 30° and θ = 45°). For b/h = 4, the Present Model shows a slightly lower buckling load compared to B Adim [7], but it is higher than Reddy [131] and significantly higher than the First-Order Shear Deformation Theory (FSDT) [24] illustrated in Table 3. As b/h increases to 10 and 100, the results from the Present Model converge more closely with those from B Adim [7] and Reddy [23], especially at higher values of b/h, where the difference between the methods becomes minimal. The FSDT [24] consistently underestimates the buckling load compared to the other methods, highlighting the importance of higher-order theories like those used in the Present Model, B Adim [7], and Reddy [23] for more accurate predictions in thin laminates.

RESULTS AND DISCUSSIONS

The literature survey made clear how important it is to investigate the static and dynamic analysis of composite materials using various plate theories. In this study, the impact of trapezoidal plate edge condition with various layup strategies on laminated panel vibration behavior is investigated. A simply supported laminated square plate with or without starting load is subjected to vibration analysis. After reviewing these findings, a 10 × 10 mesh size was chosen, and this mesh size was used for the whole investigation.

This study aims to investigate the effect of sinusoidal and inverse sinusoidal loads on the vibration and buckling behavior of laminated composite symmetrical and unsymmetrical trapezoidal panels using a higher-order shear deformation theory (HOSDT).

Vibration Behaviour of Trapezoidal Plates Exposed to In-Plane Edge Loads

The effect of Sinusoidal in-plane edge loads on the vibration behavior of various symmetric trapezoidal plate (STP) configurations is investigated by considering cross-ply layup schemes, with the results presented in Figure 6. The plate under consideration has an aspect ratio of a/b = 1, with all four sides simply supported. It is evident from Figure 6 [1], that the non-dimensional frequencies (ϖ) at zero load indicate the fundamental frequencies of different configured STP. As the trapezoidal shape ratio b_1/b increases, the fundamental frequency continues to decrease and eventually drops to zero at the buckling onset. The IPEL at which the frequency diminishes to zero is termed the buckling load. This method, which involves a dynamic approach for determining the onset of γcr, can be attributed to the decrease in panel stiffness with the increased cutout size. Notably, for any non-dimensional load, b1/b = 0.5 shows the highest buckling resistance and natural frequencies compared to all other trapezoidal shape ratios.

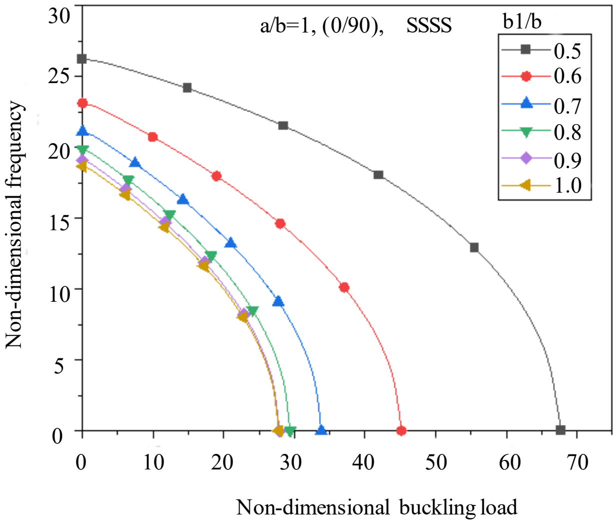


Figure 6. Variation of frequency parameter (ϖ) vs non-dimensional load (γ_{cr}) under different symmetrical trapezoidal shape [1].

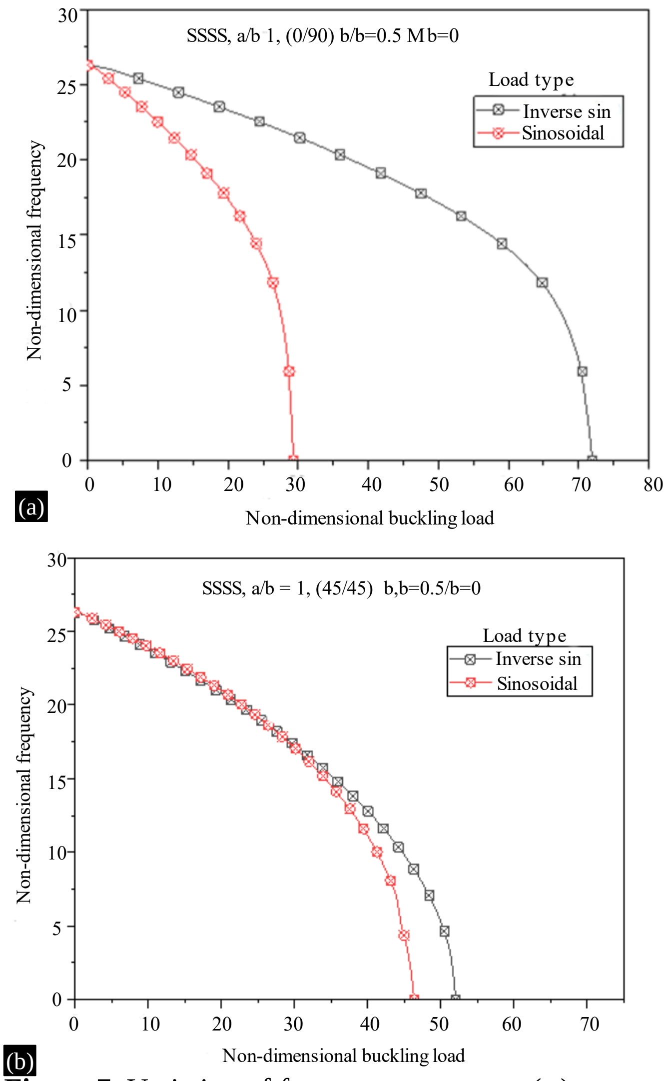


Figure 7. Variation of frequency parameter (ϖ) vs non-dimensional load (γ_{cr}) under different loading cases with symmetrical trapezoidal shape [1].

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The influence of the magnitude of different edge loading on the non-dimensional frequencies of trapezoidal laminated STP cross-ply and angle-ply plates is investigated by considering simply supported boundary conditions, and the results are depicted in Figures 7 (a) and 7 (b). The frequencies at zero load represent the fundamental frequency. This method involves a dynamic technique to find the onset of γcr. For a given UDL, sinusoidal, and inverse sinusoidal—where the frequency of vibration decreases with the increase in load. The highest frequency is observed for angle-ply symmetric trapezoidal plate, and it decreases with an increase in edge load, with the lowest frequency observed for cross-ply laminate, as seen in Figures 8. It is also important to note that the angle-ply trapezoidal plate (STP) shows marginally higher fundamental frequency and buckling resistance under the same conditions.

Effect of Sinusoidal Load And Cutout Ratio on Buckling Behaviour

The influence of the kind of load and circular cutout size on γ_{cr} in a $(0/90)_s$ and $(\pm45)_s$ cross and angle ply laminate is shown in Figure 8. The b_1/b ratios are varied from 1.0 to 0.5, and the cutout size is changed from 0.0 to 0.60. With a trapezoidal form ratio of 0.5 and a zero cutout ratio, the critical buckling force is at its maximum. The graph also makes it abundantly evident that the critical buckling load varies significantly depending on the ply orientation. Trapezoidal form ratios and the ply angle are altered by the buckling stress as cutout ratios rise. Under sinusoidal edge loads, the results with a ply-oriented laminate symmetrical panel of $(0/90)_s$ are shown in Figure 8(a), and the results with a laminate symmetrical panel of $(\pm 45)_s$ s are shown in Figure 8(b). Figure 8 illustrates how the influence of the γ_{cr} diminishes as the trapezoidal form ratio increases.

Effect of Inverse Sinusoidal Load and Cutout Ratio on Buckling Behaviour

Figure 9 illustrates the influence of circular cut-out size and load type on γ_{cr} in $(0/90)_s$ and $(\pm45)_s$ cross and angle ply laminates. The cut-out size ranges from 0.0 to 0.60, while b_1/b ratios range from 1.0 to 0.5. Notably, when the trapezoidal form ratio is 0.5 and the cutout ratio is zero, the critical buckling force is notably high. The graphs demonstrate a consistent decrease in critical buckling load for both ply orientations as the cut-out ratios increase. Furthermore, the impact of buckling stress varies with trapezoidal shape ratios and ply angles as cut-out ratios rise. Figures 9(a) and 9(b) depict the outcomes under inverse sinusoidal edge loads for laminate patterns with $(0/90)_s$ ply orientation and $(\pm45)_s$ unsymmetrical panel, respectively. As observed in Figure 9, an increase in trapezoidal form ratio results in a corresponding increase in γ_{cr}.

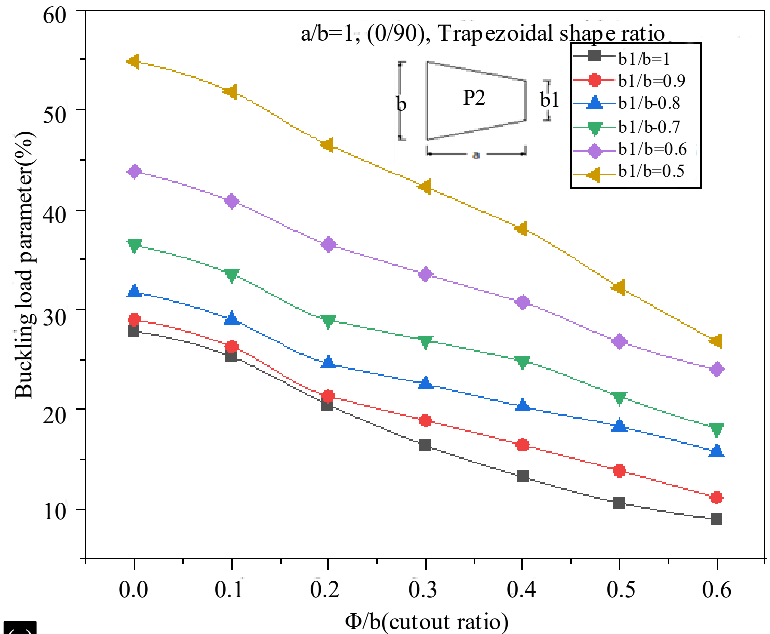
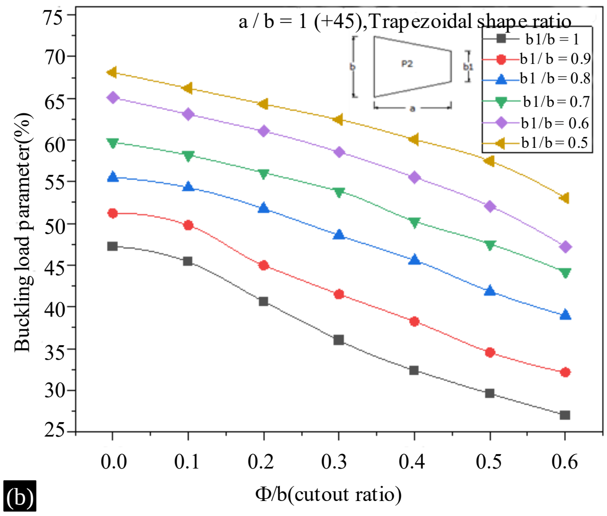
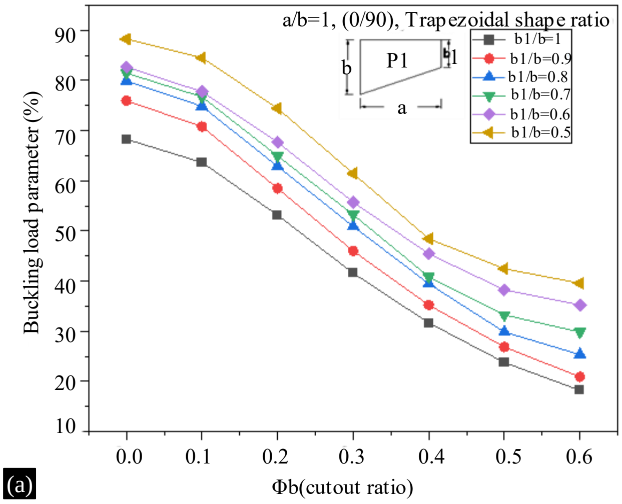


Figure. 8(a): Buckling behaviour different cutout ratio



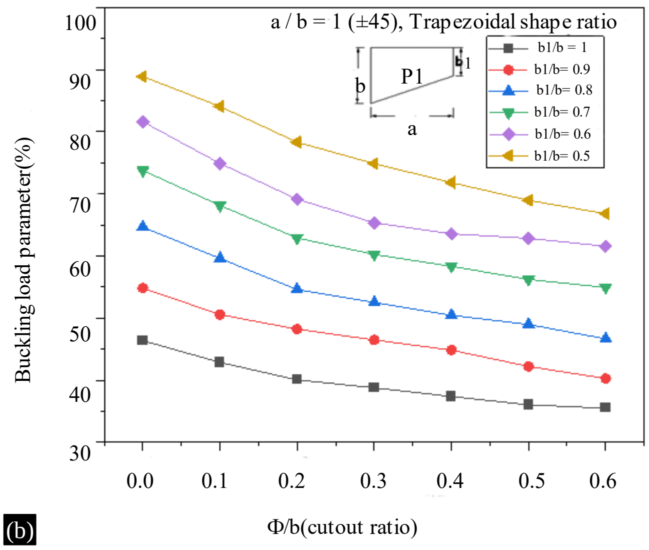
(b)

Figure. 8(b): Buckling behaviour different cutout ratio.



(a)

Figure 9. (a): Buckling behaviour different cutout ratio



(b)

Figure 9. (b): Buckling behaviour different cutout ratio

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Effect of Boundary Conditions and Trapezoidal Shape on Buckling Behaviour

Figure 10 illustrates the influence of trapezoidal shape and boundary conditions (bc's) on γ_{cr} in $(0/90)_s$ and $(\pm 45)_s$ cross and angle ply laminates. The trapezoidal shape ratio ranges from 0.5 to 0.10, while cutout ratio is maintained 0.2. Notably, when the trapezoidal form ratio is 0.5 and the cutout ratio is 0.2 with the different bc's, the critical buckling force is notably high. The graphs demonstrate a consistent decrease in critical buckling load for both ply orientations as the trapezoidal shape ratios increase. Furthermore, the impact of buckling stress varies with boundary conditions and ply angles as trapezoidal shape ratios rise. Figures 10(a) and 10(b) depict the outcomes under sinusoidal edge loads for laminate patterns with $(0/90)_s$ ply orientation and $(\pm 45)_s$ symmetrical trapezoidal panel. As observed in Figure 11, CCCC bc's found highest buckling loads with $(0/90)_s$ ply orientation and $(\pm 45)_s$ symmetrical trapezoidal panel as compared with SSSS and other bc's results in a corresponding increase in γ_{cr}.

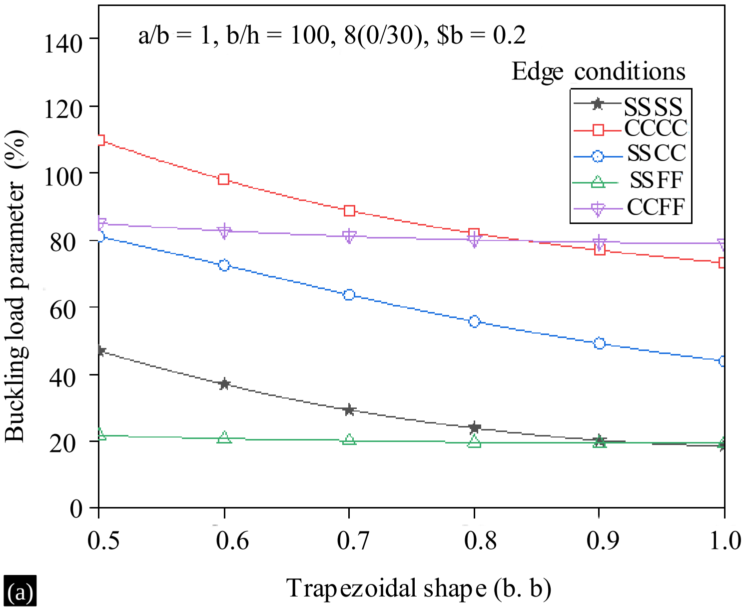

Figure 10. (a): Buckling behaviour at different bc's

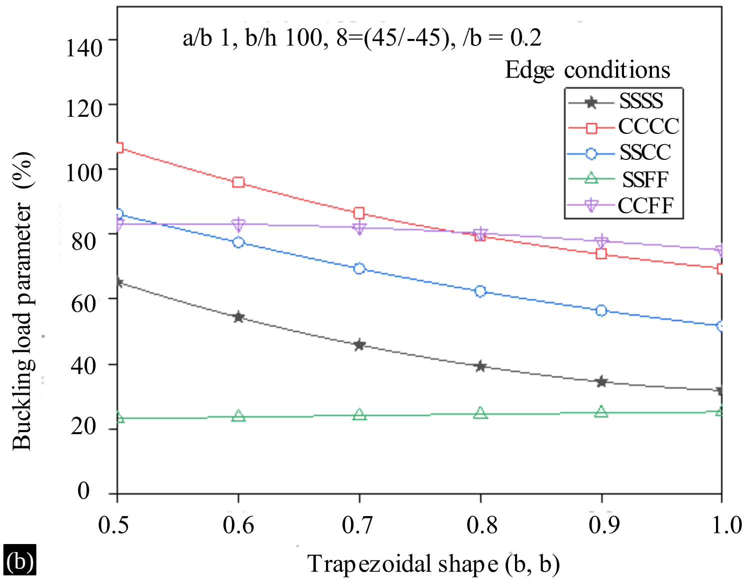

Figure 10. (b): Buckling behaviour at different bc's

CONCLUSIONS

This study comprehensively explores the effects of sinusoidal and inverse sinusoidal in-plane edge loads on the vibration and buckling behavior of laminated composite symmetrical and unsymmetrical trapezoidal panels using higher-order shear deformation theory (HOSDT). The results indicate that the panel's shape, ply orientation, cutout size, and loading type significantly influence its stability and dynamic response.

For sinusoidal edge loads, symmetrical trapezoidal panels with higher aspect ratios demonstrated superior buckling resistance and higher fundamental frequencies. In contrast, inverse sinusoidal loads showed a consistent decrease in critical buckling loads as the trapezoidal form ratio increased, especially in panels with larger cutout sizes. The findings reveal that symmetrical panels with cross-ply and angle-ply configurations exhibit different buckling behaviors, with angle-ply laminates generally showing higher buckling resistance and natural frequencies.

Overall, the study highlights the necessity of accounting for load type, panel geometry, and ply orientation when designing laminated composite structures to ensure their optimal performance under varying loading conditions. These insights contribute to the development of more efficient and reliable composite panels for advanced engineering applications.

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