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Buckling Analysis of Laminated Composite Plates with Delamination Using an Enhanced Hexahedral Solid-Shell Finite Element

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Abstract: This study aims to assess the buckling behaviour of laminated composite plates, both with and without delamination, with an enhanced hexahedral solid-shell finite element framework grounded in the advanced Hexahedral Solid-Shell Finite Element method. This technology addresses significant numerical issues, including volumetric locking and transverse shear, hence ensuring high accuracy in forecasts throughout the process. The critical buckling loads of virgin plates with symmetric and quasi-isotropic layups were examined and contrasted with those of plates exhibiting various delamination sizes and configurations. The data indicate that symmetric layups exhibit greater buckling loads; however, the presence of delamination significantly affects buckling capacity, especially for bigger delamination located near the centre of the structure. These findings illuminate the structural behaviour of delaminated composites under compressive stresses applied within the material's plane.

Keywords: *Laminated Composite Plates; Buckling Load; Enhanced Hexahedral Solid-Shell Finite Element; Assumed Natural Strain.*

INTRODUCTION

It is common knowledge that delamination is an extremely common reason for the failure of laminated composite structures. It can also result in a significant decrease in the stiffness and load-carrying capacity (LCC) of these structures, particularly when they are subjected to inplane compression and shearing. Initial flaws, in-service damages, and excessive stress concentration in the region of geometric or material discontinuities are all potential causes of delamination (Gangwar, Agrawal, & Joglekar, 2021). Delamination can also be caused by discontinuities in the material. In addition, when the material is compressed in the plane of the structure (Mondal, & Ramachandra, 2020)., the delamination may expand fast, which may result in a failure of the structure. Numerous studies, including analytical, numerical, and experimental investigations, have been conducted in recent years with the purpose of gaining an understanding of the behaviour of laminates that contain delamination when they are in the buckling along with post-buckling phases. Both the influence of extension-bending coupling (Karimi and Amin Yazdi, 2023) and the bearing of transverse shear deformation (Ameri et al., 2020) on the buckling and post buckling of delaminated composites are taken into consideration in some of this research. To model the layered structures, several different approaches have been proposed. One of these approaches is the equivalent singular layer model, which includes the first order shear deformable theory along with the higher order shear deformable theory (HSDT) (Xia, et al., 2024). These models are simple to implement, and the count of degrees of freedom that are required is not dependent on the count of layers (Hebbar et al. 2020).

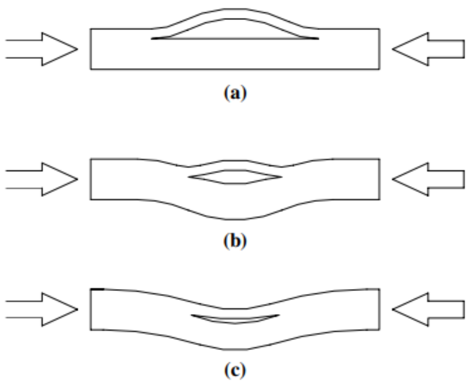

Figure.1 Buckling modes of delaminated composite plates (schematic view): (a) local mode, and (b) mixed mode along with (c) global model (Deng, et al. 2020).

Despite the fact that the HSDT provides a satisfactory description of the displacement and stress field in isotropic or low modulus ratio situations (Ansari, Hasrati, & Torabi, 2020)., it is possible that it may not provide correct findings when the modulus ratio is significant. It has been discovered that layer-wise models Ren, Zhao, and Zhang (2020) and Khoshgoftar, Karimi, and Seifoori (2022) can contribute to the development of superior solutions for such a need. The plate and shell type models are usually reduced surface models. These models are always this type. When delamination is present, they become more difficult than they were before (Deng, et al. 2020). The application of solid shell formalism with a three-dimensional aspect, which was previously utilised to investigate the delamination problem, became less difficult (Mittelstedt, et al., 2022) The utilisation of these components results in the emergence of locking issues: shear locking along the volumetric and transverse planes. Through the utilisation of decreased plate and shell, the investigation of composite structures that exhibit delamination is carried out. Solid shell elements are going to be utilised in our investigation of these issues. There have been several different approaches that have been suggested to solve this issue, with the most effective of these being categorised as mixed methods. For these formulations, it is possible to make distinct field assumptions for strain, stress, and/or incompatible displacements, which can then be subsequently incorporated into the associated functional. The assumed natural strain (ANS) methodology (Kulikov & Plotnikova, 2020) and the Enhanced Hexahedral Solid-Shell Finite Element formulation (Pfefferkorn & Betsch, 2020) are two examples of the procedures that can be derived from these methods. When using the latter approach, it is possible to avoid using the volumetric and transverse shear locking method, and it is also possible to achieve a high level of accuracy even when using distorted element forms (Jin et al., 2020). It is common knowledge that delamination is one of the most common reasons for the failure of laminated composite structures (Khan, & Kim, 2022). It can also result in a significant decrease in the stiffness and LCC of these structures, particularly when they are subjected to in plane compression and shearing. Initial flaws, in-service damages, and excessive stress concentration in the region of geometric or material discontinuities are all potential causes of delamination (Huang, & Bobyr, 2023). The grounds of this method come from the important scientific work of Pfefferkorn, & Betsch, (2020). where the strain field is enlarged with the inclusion of additional variables, usually referred to as enhancing parameters, as given by Eq. (1.1). It should be noted that these additional variables don't really have physical meaning and are eliminated at the element level:

$$E = E^c + \tilde{E} \dots \dots (1.1)$$

where E^c and $\tilde{E}$ are respectively the compatible part and the enhanced part of the Green-Lagrange tensor.

The variational foundation of the finite element tactic utilized with enhanced assumed strain fields is grounded in the well-known three field Hu -Washizu principal, which, by using Eq. (1.1), takes the following forms:

$$\Pi(u,\tilde{E},S) = \int_V \left(\psi(\tilde{E}+E^c) - S:\tilde{E}\right)dV - \Pi_{ctr}(u) = 0 \ldots\ldots (1.2)$$

$$\Pi_{ext}(u) = \int_V F_V \cdot u dV + \int_{\partial V_f} F_S \cdot u dA \ldots\ldots (1.3)$$

where ψ is the strain energy function and u and S are the displacement and the Piola-Kirchoff stress fields, respectively. Also, in the equations appear the prescribed body force $\boldsymbol{F}_V$ and surface traction F_S.

Invoking the orthogonality condition:

$$\int_V S:\tilde{E} dV = 0 \ldots\ldots (1.4)$$

Reducing the count of independent variables in the original function to just two, the weak form of this modified reduced function may be obtained with the direction derivative leading to:

$$G(u,\tilde{E}) = \int_V S:\left(\delta E^c + \delta\tilde{E}\right)dV - \int_V F_V \delta u dV - \int_{iV_J} F_S \delta u dA = 0 \ldots\ldots (1.5)$$

This equation must be linearized to take the following form:

$$DG.(\Delta u, \Delta\tilde{E}) = \int_V \delta E^c : \mathbb{C}:\left(\Delta E^c + \Delta\tilde{E}\right)dV + \int_V S:\Delta\delta E^c dV + \int_V \delta\tilde{E}:\mathbb{C}:\left(\Delta E^c + \Delta\tilde{E}\right)dV \ldots\ldots (1.6)$$

where $\mathbb{C}$ is the elasticity tensor. Eq. (1.6) will be solved by the Newton-Raphson method.

Enhanced Hexahedral Solid-Shell Finite Element method

The compatible strain-displacement relations matrix at the element level is given by

$$\mathbf{B}_I = \begin{bmatrix} g_1^T \, N_{t,1} \\ g_2^T \, N_{t,2} \\ \sum_{L=1}^{4} \frac{1}{4}(1+\xi_L^1\xi^1)(1+\xi_L^2\xi^2) g_3^L \, N_{t,3}^L \\ g_2^T \, N_{t,1} + g_1^T \, N_{t,2} \\ \frac{1}{2}\left[(1-\xi^2)\left(g_3^{B^T} N_{t,1}^B + g_1^{B^T} N_{t,3}^B\right) + (1+\xi^2)\left(g_3^{D^T} N_{t,1}^D + g_1^{D^T} N_{t,3}^D\right)\right] \\ \frac{1}{2}\left[(1-\xi^1)\left(g_3^{A^T} N_{t,2}^A + g_2^{A^T} N_{t,3}^A\right) + (1+\xi^1)\left(g_3^{c^T} N_{I,2}^C + g_2^{c^T} N_{t,3}^C\right)\right] \end{bmatrix} \ldots\ldots (1.7)$$

where $L_1, L_2, L_3, L_4, A, B, C$ and D are given in Fig. 1.1

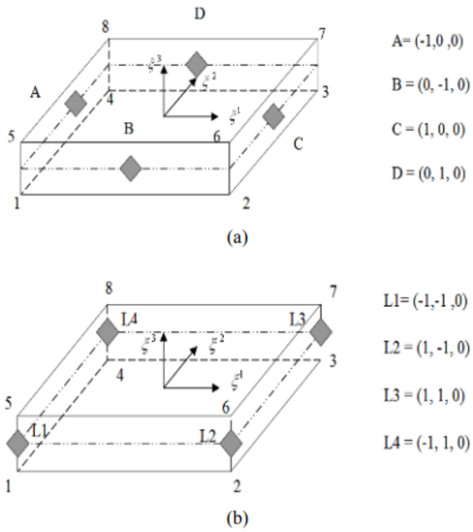

Fig.2 Strain interpolations points: (a) Shear strain; (b) Transverse strain.

From this formulation, we obtain two types of elements the solid element and the solid shell element. The basic equation of the buckling analysis is in the form of an eigenvalue problem:

$$(K_e - L^T H^{-1} L)\phi = \lambda K_G \phi \ldots\ldots (1.8)$$

where ϕ is the generalized global displacement eigenvector. This eigenvalue problem is solved using the subspace iteration method. The lowest eigenvalue λ_1 derived from the subspace iteration approach represents the buckling load, while its associated eigenvector denotes the appropriate buckling mode**.**

Research Problem

De-laminations in composite laminates can lower rigidity and disrupt material balance in symmetric laminates. De-laminations can rapidly increase under post-buckling pressures, reducing structural strength and resulting in disastrous collapse.

Objective

To investigate the interplay between local and global buckling behaviours of laminated composite plates across several factors, comprising delamination size, and aspect ratio, and width-to-thickness ratio, and stacking sequences, along with the positioning of delamination and multiple delamination's.

METHODOLOGY

Enhanced Hexahedral Solid-Shell Finite Element method

The Enhanced Hexahedral Solid-Shell Finite Element Method was utilized to analyze the buckling behavior of laminated composite plates with and without delamination's. This approach employed eight-node hexahedral solid-shell elements, providing a detailed three-dimensional representation of the plates. The Enhanced Hexahedral Solid-Shell Finite Element Method was integrated into the formulation to overcome numerical challenges such as transverse shear and volumetric locking, ensuring precise and reliable results even in the presence of distorted element geometries. Square laminated plates with varying aspect ratios were modeled, and their critical buckling loads were evaluated under uniform in-plane compressive loads. The study included pristine plates to establish baseline behavior and plates with delamination of varying sizes and positions to assess their impact on structural stability. Delamination was modeled as through-the-width discontinuities, with parameters such as size (10%, 20%, and 40% of the plate area) and position (center and edge) systematically varied. Numerical results were obtained and analyzed using Newton-Raphson iterative methods to ensure convergence of the non-linear finite element equations.

Model Parameters

Geometry: Square laminated plates with dimensions 500 mm × 500 mm × 5 mm.

Material Properties

1. $E_1 = 135\text{GPa}, E_2 = 10\text{GPa}$.
2. $G_{12} = G_{23} = 5\text{GPa}$.
3. $\nu_{12} = 0.25$.

Stacking Sequences: Symmetric ($[0°/90°/90°/0°]$) and quasi-isotropic ([45% $/-45°/45°/-45°]$) layups.

Boundary Conditions: Simply supported edges subjected to uniform in-plane compressive loads.

1 Without Delamination's: Pristine plates were analyzed to establish baseline critical buckling loads for various stacking sequences and aspect ratios ($a/b = 1.0, 1.5$).

2 With Delamination's: Delamination's were modeled as through-the-width discontinuities at the mid-plane. Delamination sizes ($10\%, 20\%$, and 40% of plate area) and positions (center and edge) were studied to determine their effect on buckling loads.

RESULTS AND FINDINGS

Buckling Loads Without Delamination

Table.1 Buckling loads without delamination

Stacking Sequence	**Aspect Ratio (a/b)**	**Critical Buckling Load (kN)**
$[0°/90°/90°/0°]$	1.0	365
$[0°/90°/90°/0°]$	1.5	280
$[45°/-45°/45°/-45°]$	1.0	345
$[45°/-45°/45°/-45°]$	1.5	265

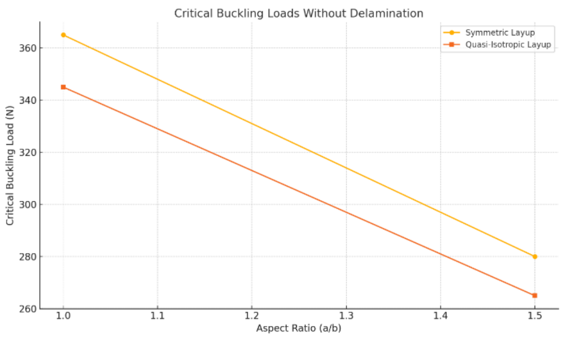

Figure.3 Comparison of critical buckling loads for symmetric and quasi-isotropic layups across different aspect ratios without delamination.

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Pristine laminated plates demonstrated superior buckling performance, consistent with the expected structural stability of undamaged composite materials. As seen in Table 1.1, symmetric layups ([0°/90°/90°/0°]) exhibited higher critical buckling loads compared to quasi-isotropic layups ([45°/-45°/45°/-45°]) for all aspect ratios analysed. For plates with an aspect ratio (a/ba/ba/b) of 1.0, the symmetric layup achieved a critical buckling load of 365 kN, outperforming the quasi-isotropic configuration by 20 kN (approximately 5.8%). This difference highlights the advantage of symmetric stacking sequences in maintaining uniform stress distribution and structural integrity under compressive loads. When the aspect ratio increased to 1.5, both layups experienced a drop in buckling loads owing to the increased slenderness of the plates. However, the symmetric layup still maintained a higher critical load of 280 kN compared to 265 kN for the quasi-isotropic layup, reflecting a similar trend of superior performance.

The variation in critical buckling loads across stacking sequences and aspect ratios is graphically illustrated within Figure 1.2. The figure clearly demonstrates the influence of layup configuration and aspect ratio on the buckling behaviour. Symmetric layups consistently provided higher buckling resistance, emphasizing their suitability for applications requiring enhanced structural stability.

Impact on Delamination with Buckling Loads

Table.2 Impact on delamination with buckling loads

Delamination Size (%)	**Position**	**Stacking Sequence**	**Critical Buckling Load (kN)**	**Reduction (%)**
10	Center	[0°/90°/90°/0°]	330	9.6
20	Center	[0°/90°/90°/0°]	300	17.8
40	Center	[0°/90°/90°/0°]	240	34.2
20	Edge	[0°/90°/90°/0°]	315	13.7

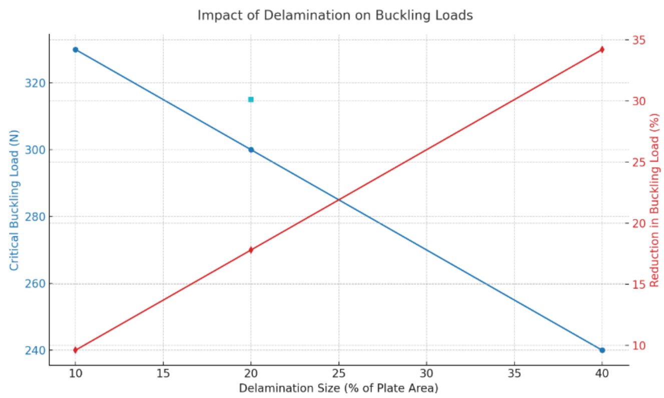

Figure.4 Impact of delamination size and position on buckling loads and reduction percentages.

The presence of delamination significantly reduced the buckling capacity of laminated composite plates. This effect was observed to intensify with increasing delamination size and was more pronounced when delamination's were located at the centre of the plate, as shown in Table 1.2. For a symmetric layup ([0°/90°/90°/0°]), the critical buckling load decreased from 365 kN in a pristine condition to 330 kN when a 10% delamination was introduced at the centre of the plate. This corresponds to a reduction of 9.6%. As the delamination size increased to 20% and 40%, the critical buckling loads dropped further to 300 kN and 240 kN, resulting in reductions of 17.8% and 34.2%, respectively. When the delamination was positioned at the edge of the plate, the reduction in buckling load was less severe. For a 20% delamination at the edge, the critical buckling load was 315 kN, with a reduction of 13.7%, compared to 17.8% for the same size delamination at the centre. This highlights the critical role of delamination location in determining the structural integrity of composite plates. Figure 1.3 illustrates the impact of delamination size and position on the critical buckling loads and reduction percentages. The central delamination cases show a steeper decline in buckling capacity as the size increases, whereas edge delamination's demonstrate a relatively moderate impact.

DISCUSSION

Buckling Loads Without Delamination

Pristine laminated composite plates exhibit superior buckling resistance, with symmetric layups outperforming quasi-isotropic configurations. The results confirm that symmetric stacking improves structural stability due to uniform stress distribution across layers. Variations in aspect ratios also influence critical buckling loads, where increasing the aspect ratio leads to a decrease in stability.

Impact of Delamination on Buckling Loads

The presence of delamination drastically reduces the buckling capacity of the plates. The extent of reduction correlates with delamination size and position:

1. Size: Larger delamination (e.g. 40% of the plate area) result in the most significant reductions, up to 34.2%, as they weaken the structural integrity of the plate.
2. Position: Centrally located delamination cause more severe reductions compared to edge delamination due to their direct impact on the critical load-carrying regions.

Stacking Sequence and Delamination

Symmetric layups remain more robust against delamination-induced buckling degradation compared to quasi-isotropic layups, which are inherently less resistant due to anisotropic stress propagation.

CONCLUSION

This study highlights the critical role of stacking sequences and delamination characteristics on the buckling performance of laminated composite plates. Symmetric stacking sequences provide superior performance under in-plane compressive loads. However, delamination, particularly large and centrally located ones, considerably weaken the structure, underscoring the need for rigorous inspection and mitigation in composite design. Future research can explore advanced mitigation techniques, such as tailored layups and smart materials, to enhance delamination resistance.

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