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A Review of Buckling Behavior of CFRP Panels Using Finite Element Method

Saud Ur Rehman Chaudhary[1], Hamza Rehman Kharal[2], Saeed Hamza[3], MD Bappi Islam[4]
[1,3]School of Civil Engineering, Chongqing University, China
[2]School of Mechanical Engineering, Chongqing University, China
[4]School of Civil Engineering, Nantong University, China
Corresponding author (Hamza Rehman Kharal, Email: hrkaharal@gmail.com)

Abstract:

One significant barrier to the widespread use of carbon fiber reinforced plastic (CFRP) materials in civil and offshore applications is the absence of universally applicable design criteria for composite structures. This issue is particularly pronounced in the context of predicting the buckling strength of composite shell structures, where designers face numerous challenges and often resort to high safety factors, thereby diminishing overall structural efficiency. Key parameters in buckling design include fiber orientations and the radius-to-thickness ratio. A crucial aspect of designing for buckling involves examining the impact of initial geometric imperfections. Both eigenvalue and incremental analyses are employed in this study, with the latter accounting for the shape and amplitude of initial geometric imperfections. These analyses help in estimating the imperfection sensitivity of CFRP curved panels. The results from these analyses are used to develop 'knockdown' factors, which are essential for design purposes. These factors provide a more accurate and reliable means of accounting for the imperfections in the material and structure, allowing for better prediction and enhancement of the buckling resistance. Consequently, this leads to more efficient and safe design practices for CFRP structures. By addressing the sensitivity to imperfections and providing reliable knockdown factors, this study contributes to overcoming some of the key challenges in using CFRP materials.

Keywords: **Buckling, carbon fiber, composite materials**

Introduction:

Fiber-reinforced composite materials are a new class of materials that have been used more frequently in recent years in a wide range of structures, including aerospace, marine, and civil infrastructure engineering domains. Because of their high strength to weight ratio and corrosion resistance, composite structures present an alluring alternative to more traditional building methods. While a good deal of research has been done on isotropic structures, there is still a dearth of systematic design data for carbon fiber reinforced plastic (CFRP) structures, which are more likely to have an impact on the infrastructure of civil engineering. This is especially valid for buckling strength. forecast, where a great deal of the work is left up to the designer. For the design of composite plate and shell structures, it is crucial to determine the critical buckling load using eigenvalue analysis and to follow the equilibrium path both before and after the limit load using non-linear analysis. Because the majority of shell structures are thin, buckling response is an important design factor.

Shells more often show unstable post buckling behaviour. However, depending on the geometry and boundary conditions, cylindrical panels under compression may exhibit either an unstable shell type behavior or a stable plate type behavior. Koiter explained that a curvature could explain the nature of post buckling behaviour, **(Koiter WT., 1956)**

$$\Theta K = \frac{1}{2\pi}[12(1-\nu^2)]^{\frac{1}{4}}\frac{b}{\sqrt{Rh}} \quad (1)$$

Eq 1. Koiter Equation

From the value $0 \leq k \leq 1$ corresponding to a flat panel to that of a full cylinder, the critical buckling stress increases. Stable to unstable post buckling behaviour will occur within this range. K=0.64, if the structure is a pinned supports along longitudinal edges. The critical buckling stress of a panel would be equal to cylindrical

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panel is the value of k ≥ 1. The panels can be considered as perfect but there are always some imperfections, which causes the reduction in the buckling strength. These imperfections can be of two types, geometric and material imperfections. The manufacturing process of lay-up in composite cylindrical shells results in geometric imperfection, which is intended to evaluate the impact of various methods of manufacturing flaw on the incline **(Chryssanthopoulos MK. et. al, 1991)**. There could be delamination as a result of imperfections caused by impact damage as well. This study deals only with the geometric imperfection damage.

In early studies, the effect of imperfections measurement or effect on the buckling behaviour is not considered, however it is important and well known for composite curved panels **(Khot NS. et, al. 1983)**. The buckling behaviour of curved fiber reinforced panels are tested under uniform end displacement and compared with numerically calculated buckling behaviour. However, the theoretical studies shows evident that the effect of anisotropic properties on both critical buckling and limit loads for the laminated curved panels. **(Zhang Y. et, al. 1983, Zhang Y. et, al. 1985) (Snell MB. et, al. 1985)** presents a thorough investigation into the behavior of an axially compressed CFRP panel. Numerous techniques are used in conjunction with numerical models to study the imperfection sensitivity. The most appropriate analogy with critical eigen modes, which are imperfection shapes, are used to obtain experimental results. In comparison to isotropic panels, the experimental knockdown factors (test load/linear buckling load) are approximately 80% or higher, indicating decreased imperfection sensitivity. The goal of this work is to use finite element analysis to present a concise formulation for non-linear composite shell elements and the post-buckling behavior of composite curved panels with initial geometric imperfection.

It is demonstrated that, in relatively thick laminated plates, the buckling load determined by the Classical Plate Theory (CPT), which is based on the Kirchhoff theory, can contain large errors **(Kim KD, 1996).** The mistakes in CPT-based buckling solutions are assigned to the transverse shear deformation not being included. It is generally accepted that anisotropic composite plates with a/h ≤ 20 cannot have their buckling loads predicted by the classical theory.

Composite Panels:

Because of their remarkable strength-to-weight ratio, flexibility, and durability, composite panels are essential to the construction of wind turbine blades. Usually, a polymer matrix like epoxy resin is combined with reinforcing fibers like carbon or glass to create these blades. The structural integrity and resilience required to withstand the dynamic loads and challenging operating conditions are provided by this combination.

Because composite materials are lightweight, longer and more effective blades can be designed, increasing the turbine's overall efficiency by capturing more wind energy. Furthermore, the fatigue loads are reduced and the blade lifespan is increased by the flexibility of composite panels.

Additionally, composite panels have outstanding resistance to corrosion, which is essential for offshore wind turbines that are situated in salty marine environments. Continuous developments in composite technology are intended to guarantee wind turbine blades' sustainable use in the generation of renewable energy by streamlining the manufacturing process, cutting expenses, and improving the blades' capacity for recycling.

Finite Element Method (FEM)

The Finite Element Method (FEM) is a numerical technique used to find approximate solutions to boundary value problems for partial differential equations. It is widely employed in engineering and physical sciences to model complex systems and solve problems that involve structural analysis, heat transfer, fluid dynamics, and more.

Basic Principles

At its core, FEM involves discretizing a continuous domain into a finite number of smaller, simpler parts called finite elements. These elements can be of various shapes, such as triangles or quadrilaterals in 2D, and tetrahedra or hexahedra in 3D. The collection of all these elements forms a mesh that approximates the geometry of the original domain. Each element is associated with a set of shape functions, which are used to approximate the solution over the element. The unknown solution is expressed as a weighted sum of these shape functions. The weights are known as nodal values and are the primary unknowns to be solved.

Steps in FEM

The finite element method (FEM) in structural mechanics adheres to a strict computational framework intended to represent the intricate deformation, stability, and failure behavior of engineering structures. The discretization of the structural domain into finite elements, such as beams, shells, or solid elements, is the first step in the process. Numerical stability and accuracy are greatly influenced by the mesh resolution, element aspect ratio, and refinement near stress concentrations. To interpolate displacement fields for each element, suitable shape functions are chosen; depending on the element formulation, these functions must guarantee compatibility, meet completeness requirements, and offer sufficient continuity to represent bending, shear deformation, or higher-order modes. In order to create element stiffness matrices, mass matrices, geometric stiffness matrices (for stability analysis), and equivalent nodal load vectors, the governing equations of structural mechanics—which are derived from the balance of linear momentum and frequently expressed through the principle of virtual work—are then transformed into their weak form and integrated over each element. These component contributions are methodically put together into a global structural framework that guarantees structural equilibrium and enforces displacement compatibility across shared nodes.

To guarantee the uniqueness and physical validity of the solution, boundary conditions peculiar to structural issues are enforced, such as fixed supports, roller limits, prescribed displacements, or applied loads. At this point, nonlinear stress-strain responses are captured when necessary by incorporating material constitutive relations, such as linear elasticity, plasticity, damage models, or orthotropic lamina behavior in composites. Robust numerical algorithms are used to solve the resulting system of algebraic equations. These algorithms range from sophisticated iterative and incremental-iterative schemes for large-scale or nonlinear problems like buckling, post-buckling response, or progressive damage evolution to direct solvers for smaller linear systems. Depending on the structural phenomenon being studied, computed displacement fields are utilized in the post-processing stage to determine stresses, strains, stress intensity factors, buckling modes, natural frequencies, or energy release rates. To assess structural performance, identify failure processes, and compare numerical predictions with theoretical or experimental results, high-level visualization tools are employed. Deformation charts, stress contours, mode shape animations, and load-displacement curves are a few examples of these methods. This meticulous procedure ensures that FEM will remain a key technique for analyzing complex structural systems, including thin-walled components, composite structures, wind turbine blades, and other high-performance engineering applications.

Advantages of FEM

Versatility: FEM can handle complex geometries and boundary conditions more easily than traditional analytical methods.

Adaptability: The method can be applied to various types of physical problems, making it a versatile tool in engineering and sciences.

Precision: By refining the mesh, the accuracy of the solution can be improved. Adaptive mesh refinement techniques allow for higher precision in critical regions of the domain.

Applications

FEM is used in a broad range of applications:

Structural Analysis: To determine stresses, strains, and displacements in structures.

Thermal Analysis: To analyze heat transfer problems.

Fluid Dynamics: To solve problems involving fluid flow.

Electromagnetic Analysis: To model electromagnetic fields and waves.

Challenges and Limitations

Computational Cost: High-resolution meshes lead to large systems of equations, requiring significant computational resources.

Complexity: The method requires careful selection of

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elements and shape functions, as well as meticulous handling of boundary conditions.

Accuracy: The quality of the solution is highly dependent on the mesh quality and the accuracy of the numerical integration.

FEM is a powerful and flexible tool for solving complex engineering problems, providing detailed insights into the behavior of physical systems. Its continued development and application are essential for advancing technology and scientific understanding.

Literature Review

Fiber reinforced composite materials are widely used now in many different fields of engineering especially in aerospace, marine and civil engineering infrastructures. They are cheaper and an effective alternative because of their resistance to corrosion and high strength to weight ratio. While a good deal of research has been done on isotropic structures, there is still a dearth of systematic design data for carbon fiber reinforced plastic (CFRP) structures, which are more likely to have an impact on the infrastructure of civil engineering. A reinforced box beam was designed to improve the bending strength in flap wise direction of wind turbine blade **(Maldonado-Santiago, Ofelia, et al. 2023)**. A three dimensional model is tested using FEM and validated with four and two points. It has been noted that displacement is decreased by 30.09% and increase stiffness to 43.31% without structural reinforcement. Furthermore, a difference of 18.98% was observed in the displacements of the beams with structural reinforcements based on the two-point bending results. A maximum error of 11.24% was found in the FEM analysis when connecting the beams' experimental results with the maximum displacement value. While a good deal of research has been done on isotropic structures, there is still a dearth of systematic design data for carbon fiber reinforced plastic (CFRP) structures, which are more likely to have an impact on the infrastructure of civil engineering. This is especially valid for buckling strength. Forecast, where a great deal of the work is left up to the designer. For the design of composite plate and shell structures, it is crucial to determine the critical buckling load using eigenvalue analysis and to follow the equilibrium path both before and after the limit load using non-linear analysis. Because the majority of shell structures are thin, buckling response is an important design factor. Using FEM data, a deep neural network was trained to precisely predict the buckling mode of imperfect cylindrical composite shells. A generative adversarial network was used in the study, and using the pix2pix deep learning algorithm, make predictions **(Xin, Ruihai. et, al. 2024)** While being far more effective, the deep learning model was still able to predict with an accuracy comparable to that of the conventional FEM.

In early studies, the effect of imperfections measurement or effect on the buckling behaviour is not considered, however it is important and well known for composite curved panels . The buckling behaviour of curved fiber reinforced panels are tested under uniform end displacement and compared with numerically calculated buckling behaviour. However, the theoretical studies shows evident that the effect of anisotropic properties on both critical buckling and limit loads for the laminated curved panels. **(Zhang Y. et, al. 1983)** presents a thorough investigation into the behavior of an axially compressed CFRP panel. Numerous techniques are used in conjunction with numerical models to study the imperfection sensitivity. Reducing the buckling load is a significant design challenge, especially as slenderness increases, which heightens sensitivity to imperfections. Cylinders with the same parameters but varying slenderness across a large sample size are addressed. In this study, seven cylindrical shells, six of which are nominally identical, are tested on two different test rigs. Their results are compared with twelve specimens of smaller radius but the same wall thickness from a previous series of tests. This study illustrates how imperfection sensitivity is influenced by the R/t-ratio. Furthermore, it demonstrates the correlation between test setup quality and the achieved buckling load **(Tobias S. Hartwich, et, al. 2024)**.

Thin-walled cylindrical shells are fundamental structures in aerospace, marine, and civil engineering, often subjected to axial compression. In this loading scenario, there is a notable discrepancy between theoretical and experimental critical loads. This gap is largely attributed to shape deviations in the shell's middle plane, commonly known as geometric imperfections. However, the discrepancies observed in some cases are so pronounced that other types of imperfections might be contributing factors. This article presents both experimental and numerical studies on how loading imperfections affect the buckling load of thin-walled cylinders. During a buckling test on a thin-walled cylinder, an unintended global loading imperfection was introduced, leading to a significant reduction in the buckling load. The load level observed was akin to that of the post-buckling load. Additionally, the article details a series of experimental studies on localized loading imperfections, which similarly resulted in substantial reductions in the buckling load of CFRP (carbon fiber reinforced polymer) cylinders. The findings underscore the critical impact of loading imperfections on buckling behavior. The results of this study exemplify some of the very low buckling knockdown factors observed in early experimental campaigns. By analyzing these outcomes, the article provides valuable insights into avoiding such critical imperfections in future experimental buckling studies. In essence, this research highlights the importance of accounting for both global and localized loading imperfections in the design and testing of thin-walled cylindrical shells. The significant reductions in buckling load due to these imperfections underscore the need for rigorous experimental protocols and advanced numerical modeling to predict and mitigate the adverse effects of these imperfections. By doing so, more accurate assessments of buckling behavior can be achieved, enhancing the reliability and safety of structures that rely on these critical components **(H.N.R Wagner, et, al. 2020).**

The load-carrying capacity of cylindrical shells under axial compression can be significantly reduced by the development of buckling deformations, which can be facilitated by initial geometric imperfections that appear as various forms of local out-of-plane deformations. Before the structure is fabricated, current methods have difficulty accurately predicting the lower bound of this capacity. Therefore, during the design phase, it is crucial to determine the kind of assumed imperfection that permits approximating these lower bounds. Five 1-meter-diameter unstiffened shells—designated W1–W5—were created, examined, and put through testing in this investigation. The test results were compared with the measured imperfection approach, worst multiple-perturbation load approach (WMPLA), single-perturbation load approach (SPLA), and a combined approach involving measured imperfections and superimposed radial point load imperfections. The results show that SPLA-based techniques are sensitive to the distribution of measured imperfections and produce higher knockdown factors (KDFs) than the test results. On the other hand, there is a strong correlation between the KDFs predicted by the WMPLA and the combined approach and the test results. Based on these comparisons, it can be inferred that the WMPLA has the ability to predict a reasonable lower bound on the buckling loads of unstiffened cylindrical shells, effectively encompassing both small- and large-amplitude measured imperfections. It is advisable to exercise caution when applying the WMPLA to the design of other thin-walled structures, as distinct processes may result in notable variations in manufacturing signatures. In order to validate this approach, future studies should carry out additional buckling tests on other types of structures **(Bo Wang, Kaifan Du, et, al. 2018).**

Under axial compression, the buckling, post-buckling, and delamination behavior of composite laminates are identified. Composite laminate specimens with through-width delamination were first subjected to compression tests, and the history of buckling and delamination propagation was noted. Thereafter, two-dimensional finite-element models were used to simulate these tests. The finite-element mesh underwent a geometrically non-linear post-buckling analysis, which included a minor degree of geometric imperfection based on eigenmodes. The growth of delamination resulting from sub-laminates buckling was simulated using the cohesive zone modeling technique. To validate the numerical model, the analysis's findings were contrasted with the experimental data. The analysis results were then analyzed to investigate the relationship between the buckling loads and the geometric parameters of the initial delamination, as well as the composite laminates' post-buckling delamination propagation behavior. The study methodically looked into how various initial delamination sizes and locations affected delamination behavior. Changes in the pre-existing delamination's geometry were found to have a significant impact on the behavior of delamination growth, mode shapes, and buckling loads. It can be specifically observed that long and shallow initial delaminations typically cause local buckling, whereas deep delaminations cause a global buckling mode **(Abebaw. A.M. et. al, 2019).**

Thin-walled shell structures, especially when designed without stiffening, are significantly influenced by imperfections, which can greatly impact their load-carrying capacity. Understanding these imperfections is crucial for accurate performance assessment and improvement. The development of a sophisticated measurement system designed to measure geometric and thickness imperfections in cylindrical structures using two laser sensors is presented. The measurement system's application, design, and functionality are meticulously discussed. The system's primary aim is to provide precise measurements of geometric deviations and thickness variations in unstiffened cylindrical shell structures. This involves capturing data with high accuracy and filtering out noise to ensure the reliability of the measurements. A critical part of the study involved evaluating the system's performance on an unstiffened isotropic test specimen. During this process, measurement noise of 30 micrometers (µm) was identified. To address this, a median filter was applied, effectively reducing the noise and enhancing the clarity of the measurement data. Despite the filtering process, the system's maximum measurement error was found to be 68 µm, indicating a high level of accuracy in the detection of imperfections. The results for the PL1 shell structure showed that the geometric imperfection magnitudes ranged between -0.317 mm and 0.299 mm. This indicates slight deviations from the ideal geometry, which are critical to understand for ensuring the structural integrity and load-carrying capacity of the shell. Additionally, the system measured the maximal thickness deviation, which varied from 0.155 mm to 0.226 mm. These measurements highlight the range of thickness variations that can occur in the manufacturing process, affecting the structural performance. The development of this measurement system marks a significant advancement in the precise assessment of thin-walled shell structures. By accurately measuring geometric and thickness imperfections, engineers and researchers can better predict and enhance the performance of these structures. The system's ability to filter out noise and maintain a low measurement error ensures reliable data, which is essential for designing more robust and efficient thin-walled shell structures. It provides a comprehensive overview of a new measurement system that significantly improves the ability to measure and analyze imperfections in cylindrical thin-walled shell structures. Through detailed evaluation and application, the system has demonstrated its effectiveness, offering valuable insights into the imperfections that impact the load-carrying capacity of these structures. This development is a crucial step forward in the field of structural engineering, providing a reliable tool for improving the design and performance of thin-walled shells **(P. Lyssakow, et. al, 2019).**

Geometry

The Finite Element Method (FEM) is frequently used to analyze the buckling behavior of Carbon Fiber Reinforced Polymer (CFRP) panels, and it is important to consider the geometry of these panels. The composite structure of CFRP panels is what sets them apart; these panels are usually made of layers of carbon fiber mat or cloth that have been impregnated with a polymer resin, like epoxy. Because of its remarkable stiffness and strength-to-weight ratio, CFRP panels are the perfect choice for industries like aerospace, automotive, and marine where high strength and lightweight are critical requirements.

Layup Configuration:

CFRP panels are manufactured with specific layup configurations, where layers of carbon fiber are stacked in various orientations relative to each other. The orientation of these layers significantly influences the mechanical properties of the panel, including stiffness, strength, and resistance to buckling. Common layup orientations include unidirectional (0°), bidirectional (±45° or ±60°), and quasi-isotropic (where layers are symmetrically distributed in orientations like [0°/90°/±45°]).

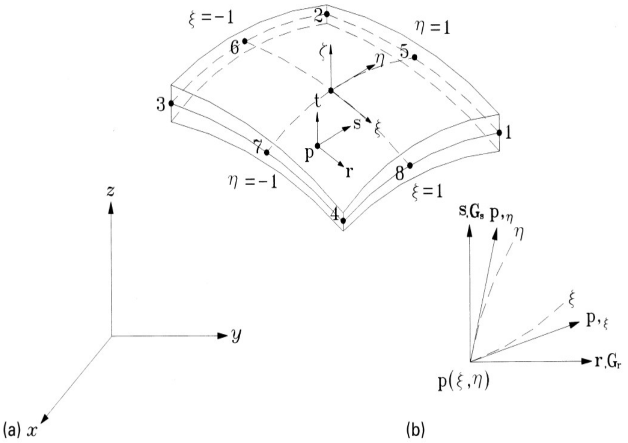

Fig 1. Layup Configuration

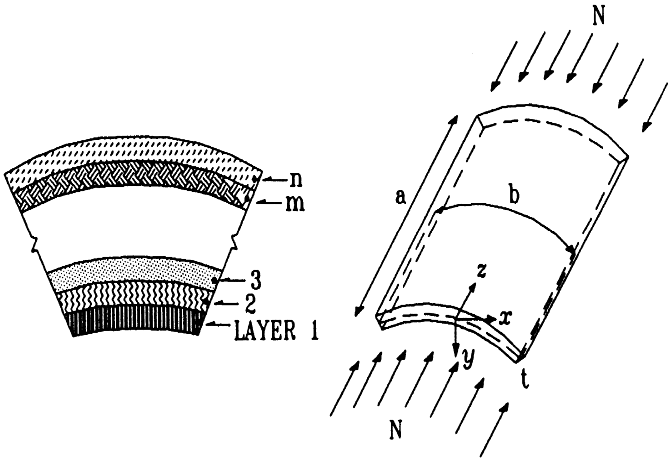

Fig 2. Geometric Imperfection

Panel Dimensions and Shape:
The dimensions and shape of CFRP panels vary based on the application requirements. Panels can range from small components to large structural elements. Typical shapes include flat panels, curved panels, and panels with cutouts or perforations, each affecting their buckling behavior differently. The thickness of CFRP panels is also critical, influencing both their stiffness and ability to withstand compressive loads without buckling.

Edge Conditions:
The edge conditions of CFRP panels, whether simply supported, clamped, or free, also impact their buckling behavior. These conditions affect how the panel deforms under load and can significantly influence critical buckling modes and load-carrying capacity. FEM simulations take into account these edge conditions to accurately predict the buckling response of CFRP panels under different loading scenarios.

Geometric Imperfections:
Like any structural component, CFRP panels may have geometric imperfections introduced during manufacturing or service. These imperfections, such as local variations in thickness, waviness, or misalignments in fiber orientation, can localize stresses and promote early onset of buckling. FEM allows for the consideration of these imperfections in modeling, providing insights into their influence on the buckling behavior and structural integrity of CFRP panels.

Integration of Structural Features:
In practical applications, CFRP panels often integrate additional structural features such as stiffeners, ribs, or reinforcements to enhance their buckling resistance and overall performance. These features alter the panel's geometric properties and can either mitigate or exacerbate buckling tendencies, depending on their design and placement relative to the panel's loading conditions.
The geometry of CFRP panels encompasses their layup configuration, dimensions, shape, edge conditions, and integration of structural features. Understanding and accurately modeling these geometric aspects are essential for predicting and optimizing the buckling behavior of CFRP panels using the Finite Element Method. This approach aids in designing lighter, stronger, and more resilient structures across various engineering disciplines where CFRP panels are employed.

Conclusions and future insights:
Ply orientation's effect on critical buckling loads is investigated in this study, which focuses on axially compressed CFRP (Carbon Fiber Reinforced Polymer) curved panels. The effect is negligible for different angle-ply panels at constant curvature; however, for cross-ply and quasi-isotropic lay-ups, the variation in critical loads rises to approximately 12%. The broad range of buckling mode shapes is a noteworthy observation with important consequences for structural code tolerances and imperfection sensitivity studies.

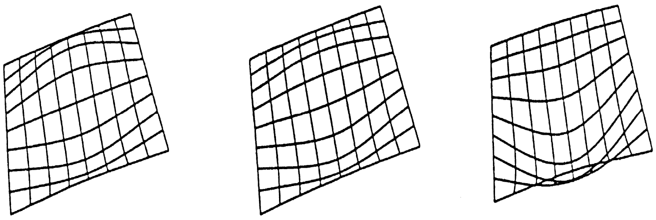

Fig 3. Mesh

To estimate knockdown factors and quantify imperfection sensitivity, incremental non-linear analyses were performed. While acknowledging the limitations of this approach, these analyses used imperfection models based on the critical mode from linear eigenvalue analysis. The results show that wide composite curved panels that are symmetrically layered and show unstable shell-type behavior have comparatively high knockdown factors when compared to their isotropic counterparts. In line with earlier research on CFRP panels, the lowest knockdown factor found is roughly 0.70. Lower factors are typically linked to low R/h ratios.

Despite these discoveries, additional experimental verification is still required because the current findings only take into account numerical analysis. In order to comprehend post-buckling behavior features for composite panels, such as Koiter's b-coefficients from the initial post-buckling analysis, theoretical work is also required. Furthermore, studies should concentrate on defining imperfection tolerances by evaluating how manufacturing processes affect the final geometry. To progress the structural application of composite materials in the civil and aerospace fields and towards validated limit state design criteria for composite shells, it is imperative to develop failure criteria that are based on experimentally observed failure modes.

This work is restricted to a parametric analysis of the influence of imperfection sensitivity on buckling capacity. Additionally emphasized is the impact that material and delamination damage have on the buckling capacity of laminated composite structures. The kinematics of material and delamination damage deformation, as suggested by Voyiadjis and Park, will be incorporated into continuum damage mechanics in subsequent work. An upcoming article will present the findings from the parametric study of laminated composite shells with material and delamination damage.

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