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A Review: Fiber Reinforced Polymer cylindrical shells subject to combined loading condition of Torsion and External Pressure

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ABSTRACT

This review paper aims to thoroughly examine how cylindrical shells made of fiber-reinforced polymer (FRP) behave when they are twisted and pushed from the outside at the same time. The growing utilization of FRP cylindrical shells in diverse industries has sparked interest, yet their performance under combined loading remains inadequately explored. The aim of this study is to present a thorough overview of the existing research landscape on this subject, encompassing experimental investigations and theoretical analyses. The review extensively covers key findings, acknowledges existing limitations, identifies gaps in current understanding, and proposes avenues for future research that could enhance both insight and design capabilities. Through a detailed examination The response of FRP cylindrical shells to concurrent torsion and external pressure, this review contributes significantly to the advancement of more effective and dependable structural design practices. This study demonstrated that the research on this area spanning decades. It emphasizes diverse materials, loading conditions, and research methods. Key themes include initial imperfections' influence on non-linear responses and buckling behavior, notably in thin-walled shells. Recent focus has been on imperfection sensitivity and their integration into design and optimization. Notably, composite materials like CFRP and FRP are crucial. Future research could delve into material effects, imperfection sensitivity, innovative design, and optimization to further advance practical applications' understanding and design techniques.

Keywords: Fiber Reinforced Polymer (FRP), cylindrical shells, combined loading, torsion, external pressure, experimental investigations, theoretical analyses, design guidelines.

1. INTRODUCTION

Shell structures are employed in many kinds of industrial and construction applications for example transportation, buildings, and pressure vessels [1]. Fiber-reinforced polymer (FRP) composites are one of the most extensively studied materials, and their uses in industries such as automotive, and construction are widely known owing to its high strength-to weight ratio, durability, and resistance to deterioration [2]. When FRP composites used in the design and fabrication of shell structures including tanks, pressure vessels, and pipes provides many advantages compare with conventional materials [3-4]. Nonetheless, the associated mechanical strength limitations in thin shell designs can eliminate some of the cost advantages, especially when experiencing compressive loadings that often cause buckling, a catastrophic failure mode leading to severe health and safety risks [5]. Although buckling has been investigated for more than 100 years, modern design methods make use of theoretical results (for optimum structures) and knockdown factors (for unanticipated defects or loading and boundary conditions). Although extensive research has been conducted to demonstrate FRP's effectiveness in enhancing the load capacity of cylindrical shells, the exact mechanism by which FRP counters buckling modes remains elusive [6]. Additionally, in the analysis of cylindrical shells subjected to shear, axial, and circumferential compression, accounting for local buckling is essential, given its frequent occurrence [7]. The torsional stability of cylinders has long been tested across different ranges, though inconsistencies have persisted because of the multiple buckling modes observed.

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Research Article

Moreover, theoretical research has contributed to extending methods for stability analysis under axial and surface pressure conditions [8].

It is important to design and analysis of FRP cylindrical shells, understand its behavior when subjected to combined torsion and external pressure loading. In practical applications these shells are mostly exposed to several types of loading simultaneously. As one example, pressure vessels can experience both internal pressure, and flexure by fluid flow and rotation. By understanding the behavior of the FRP cylindrical shell in these situations, engineers can confidently predict response and therefore the design safety. This knowledge is vital to optimize designs, to guarantee safety and to avoid failure. Through studying the behavior of such structures under combined loading, designers in engineering practice are able to produce more efficient, reliable and economic designs which satisfy performance specifications with minimal use of material.

This review aims to deliver an in-depth examination of recent progress related to FRP cylindrical shells subjected to the simultaneous actions of external pressure and torsion. By surveying research on structural responses, theoretical modeling, experimental investigations, and design methodologies, the paper seeks to enhance the foundation for more accurate predictive models of these structures. By means of a thorough study of the results of more than one hundred prior investigations on this subject, this paper brings to light and consolidates prospective new ideas that can be the theme of future analytical or numerical models to predict the response of cylindrical shells made from different kinds of materials and under various loads. The paper aims to fill the gaps and give a review of the existing and novel frond-end models for the prediction of the resistance of FRP cylindrical shells to the combination of torsion and external pressure. It has potential also in finding more accurate future calibration models and in enhanced technical understanding and uncertainty are highlighted among the challenges facing the community. The present work also conducts a comprehensive examination of the finite element (FE) analysis procedures to identify major failure modes and to propose better design criteria. Besides, a review gives a vision of new research directions and possible strengthening and the issue of knowledge current productivity in a critical way is systematically examined. The primary objective of this paper is to establish new design guidelines for cylindrical shells subjected to combined loading, prioritizing safety in industrial applications. Special attention is given to the performance of torsion and FRP cylindrical shells, with the expectation that the findings will contribute to advancing predictive modeling and refining design approaches.

2. BACKGROUND AND THEORY

Therefore it's necessary that FRP cylindrical shell can resist both the torsion and the external pressure because we apply it to the design. Externally to internally pressure stability is the ability of a pressure vessel to not collapse or crumble under the stress imposed by such pressures [9]. b) External Pressure and Torsion of FRP Cylindrical Shells - Theory The classical thin shells theory is widely used in cylindrical shells torsion study and the shell is also assumed a solid body with constant thickness. This assumption assumes that the shell is at pure torsion and little distortion is considered for the shell relative to its size. [10]. The topic on the floating of circular cylindrical shells when the DMV theory is implemented is being investigated quite a lot. This approach takes into account circumference stress along with axial stress for shell buckling. The DMV model originates from the thought of a uniform external pressure on the shell as well as small deformation produced by the shell [11]. Over the past years, numerical approaches have been extensively used to study the buckling phenomena in shell structures. Among these, Finite Element Analysis (FEA) has proven to be one of the most effective tools for accurately representing the intricate geometries and material behaviors of cylindrical shells [12]; [13–14]. The upcoming paragraphs offer an overview of experimental studies focused on advancing analytical and numerical models to simulate cylindrical shell responses. The researchers are categorized according to their research activities, experimental investigation versus theoretical modeling being one of the categories. In each section there is a comprehensive discussion including assumptions, procedures, data, and validation exercise. This also furthers the understanding of the pros and cons of the various modeling strategies and the acquisition of an overall picture of the methods used in literature. Except for few investigations tackling this topic, the present work focuses on ascertaining the contribution of FRP cylindrical shells to the combined action of the external pressure and torsion forces.

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3. EXPERIMENTAL INVESTIGATION

Extensive research has been undertaken to examine how imperfections influence the mode and progression to catastrophic failure in clamped-less cylindrical shells under uniform external pressure, with variations in aspect and slenderness ratios. The influence of imperfections, essential boundary conditions, and welding sequences on the critical buckling stress of the shells have been thoroughly examined. The stability of thin-walled members is much affected by imperfections in geometry, as mentioned in the texts of some publications [15–17]. The discussion briefly covers the application of limit analysis in depicting the influence of geometric mode variations on the critical loading of thin-walled circular cylindrical shells. Imperfections caused by material memory, forming procedures, and localized inconsistencies are key factors leading to reductions in structural load capacity. In the industrial sector, manufacturing and welding defects are commonly observed and greatly affect collapse pressure. The aspect ratio, slenderness ratio, material characteristics, and initial imperfections are identified as the principal parameters impacting buckling performance [18].

An experimental study of cylindrical shells under different loading conditions has also been carried out to consider the effect of defects in a more detailed manner. Shell buckling is also an intuitive concept that is usually easy to formulate, since the majority of work in the field is focused on circular cylindrical, conical, or spheroidal shells, which benefit from available experimental data. A significant disparity hovvever often separates new experimental results from the theoretical predictions, especially for axially loaded cylinders, where the predicted buckling loads are considerably in excess of the observed values, by nearly a factor of three. Differencesbetween hydrostatic and torsional loadings are also less relevant than the first ones. Previous studies of shell buckling focused on single loading singularities, such as bending, axial, torsion, and hydrostatic pressure. Many studies on small deflection were carried out to consider the effects of different loads either by Timoshenko's equilibrium equations or by Donnell's eighth order equilibrium equation. Moreover, within missile and aircraft design, the shell-stability theory has been widely used, and thus the combined influence of internal pressure and different load types is thoroughly studied in the present article. Increasing interests in optimum design and submarines have made the problem of uniform external radial or hydrostatic loading more relevant [19]. The behavior of thin CFRP laminates under torsion and tension was explored through both theoretical and experimental methods by Meyer-Piening et al. (2001). Showkati and Ansourian (1995) previously investigated the influence of fundamental boundary conditions on the buckling behavior of shallow cylindrical shells subjected to uniform external pressure, examining critical buckling pressures for various laminate configurations. The results of their work indicated that cylinders that were prone to defects under axial compression might not be as sensitive to simultaneously loading conditions, and the stiffness eccentricity of lamination greatly contributed to the value of axial buckling load [21]. Caution is necessary when interpreting this result, as it serves only for comparison. Hornung and Saal (2002) analyzed how imperfections influence the buckling strength of practical tanks and compared their outcomes to standard codes [22]. Similarly, Abramovich et al. [23, 24] and Wang et al. (2002) conducted experimental evaluations of stiffened cylindrical shells, factoring in various boundary conditions and geometric imperfections. Furthermore, Schneider and Brede (2004) [24] applied nonlinear finite element methods to study the buckling resistance of geometrically imperfect cylindrical shells. In their 2007 study, Teng and Hu developed the floating-curtain model and proved that the wrapping of fiber-reinforced polymer (FRP) jackets over hollow steel tubes was efficient in increasing strength and ductility. They validated their findings through axial compression testing of FRP-confined steel tubes, along with finite element simulations of FRP-jacketed thin cylindrical shells under axial compression and internal pressure. The hierarchical power series iterative solution indicated that the additional earth weight effects could be attributed to prior work [25], demonstrating that FRP jacketing serves as a reliable reinforcement technique for tubular structures, reducing buckling susceptibility. Lo Frano and Forasassi (2008) also studied the buckling of cylindrical shells with complex defects like out-of-roundness and weld misalignment, reporting their results extensively. Their work showed that welding imperfections significantly influenced the buckling behavior of shell specimens [26]. Research continues to emphasize the major role of welding defects and geometric imperfections in determining buckling loads, with numerous experimental and theoretical studies providing further clarification on these effects.

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These studies have yielded valuable information about shell performance under different conditions and have enhanced design and retrofit methods.

To obtain a complete picture of shell buckling it is important to take into account the effects of combined loadings. Now the buckling of the cylindrical shells has been studied a lot, including different external and internal pressures as well as the bending moment cases. Ramadan et al. (2010) and Batikha et al. conducted studies on the response of columns exposed to combined external and internal pressures along with bending moments. The results indicated that internal pressure supports the increase of the critical buckling load, while external pressure adversely affects it. Furthermore, external pressure promotes cross-sectional opalization, severely lowering both the buckling moment and the critical curvature, whereas internal pressure acts to reduce the extent of opalization. As well as an increase in the local (buckling moment) and overall (theoretical critical curvature) buckling performance.

Maali and her coworkers (2012) had a study in which welding-induced defects in conical shells were found to actually stabilize and improve their collapse strength [30]. In line with this, Fatemi et al. (2013) conducted research examining the influence of different structural defects, such as rumpling induced by uniform external pressure. Their study concluded that welding-induced geometric imperfections diminished the local buckling strength of these structures. The identification of the most effective imperfection in the given interval as well as the corresponding influences on the distortion and the post-buckling aspect depending on cross-section, depth of imperfections, R/t and H/R were also studied through the buckling and post-buckling response [31]. Ghazijahani et al. (2013) investigated the acoustic and local buckling effects on cylindrical shells of elastic behavior under the influence of limited forming and uniform pressure both in local and global ways. In particular the authors in the works tried to explore how the initial sectional non- circularity caused by bending, can affect the yielding of these type of shell under equal external pressure which led them to a derived cross-sectional moment interaction equation [31]. In a previous publication, Vakili and Showkati (2016) resolved ambiguities regarding the inelastic buckling phenomenon in cylindrical shells exposed to high levels of internal pressure and axial loading, typically termed "elephant foot" or pressure squashing buckling. The use of FRP composite as a reinforcement to steel cylindrical shells and the verification of its applicability by the method described may be the best solution for the repair of a cylindrical shell tank from this point of view. The work by Wang et al. (2019) does a lot of tests so as to find the knockdown factors of the geometric imperfections in cylindrical shells of revolution under axial compression. They have made a comparison of several methods, such as the measured imperfection approach, the single perturbation load method (with one perturbation shape applied to the structure), the least favorable multiple perturbation load method (with several perturbations applied simultaneously), and some other method which was called coupled, which is independent. Following their results, it was concluded that the WMPLA and the Combined Approach correspond to the lowest possible values for the failure loads of the unstiffened cylindrical shells with very high accuracy. However, it was still their view that the outcomes for other structures may be different due to their different manufacturing characteristics [32].

The behavior of cylindrical shells under combined loading, among other topics, is widely covered in numerous researches that discuss things such as the change that initial imperfections bring to the buckling behavior, the application of fiber-reinforced polymer (FRP) jackets for their reinforcement and retrofitting as well as the capacity of designing and retrofitting strategies employing FRP composites. For instance, Ramadan et al. (2010) and Batikha et al. (2008, 2009) focused on the instability behavior of cylindrical shells subjected simultaneously to external pressures as well as bending loads and internal. They found that these loads have an intricate relationship with each other, thus, the internal pressure is shown to be beneficial in the shell's stability, while the external pressure only brings a slight decrease in the critical buckling load. Among the observations was the deformation of the cross-sectional shape due to applied external forces which led to significant ovalization and so, the moment of resistance of the shell and thus the buckling load values became smaller. On the other hand, pressure forces had the ability to deform the cross-section, and hereby, they played a role in taking both the moment of resistance and critical curvature values to the upper side.

Maali et al., in their 2012 research, analyzed conical shells that suffered from defects because of welding and discovered that the latter had the most adverse impact on the stiffened panels' stiffness and their resistance to buckling [30]. Additionally, the study by Fatemi et al. (2013) was aimed to investigate the role of imperfections in

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the structural strength of thin-walled cylindrical shells under uniform external pressure. According to the study, geometric flaws introduced by welding are the biggest drivers behind the loss of buckling resistance and such factors as cross-sectional geometry, imperfection depth, and the R/t and H/R ratios are significantly the ones that influence both the buckling and the post-buckling performance [18]. Ghazijahani and Showkati (2013) conducted a comparative study on the buckling behavior of slender cylindrical steel shells under the combined effects of bending and external uniform pressure. Their findings revealed that initial geometric imperfections induced by bending significantly affect the stability of the shells under external pressure. To generalize these observations, they introduced an interaction formula [31]. Vakili and Showkati (2016) discussed the inelastic elephant foot buckling phenomenon in cylindrical shells due to increased internal pressure and axial compression. They presented a new FRP composite technology to strengthen steel cylindrical shells that the numerical analysis the definite advantage of the retrofitting the cylindrical shell tanks [13]. Wang et al. (2019) studied the influence of initial geometric imperfections on the knockdown factors for cylindrical shells subjected to an axially compressive load. They made the evaluation of several prediction methods for the lower bounds of the carrying capacity, from which the WMPLA and Combined Approach were good options that show more certainty in the failure loads of unstiffened cylindrical shells. The writers were also cautious to admit that the results of their experiments are not easily applicable to other manufacturing technology strengths [32]. They also highlight these studies, which demonstrate that the collapse analysis of shell structures should be subjected to multi-axial loading. Additionally, they highlighted the benefits of using FRP jackets for reinforcement and retrofitting, examined the influence of imperfections on the buckling response, and discussed future strategies for retrofitting and designing with FRP composite materials. They also noted that internal pressure can enhance buckling capacity, whereas low external pressure poses significant risks to structural stability when considering buckling loads. The joint effect of variations in the load and the imperfections is really complex and should be considered to more accurately predict buckling behavior, i.e., for the case of multi-load and defect conditions. The different load types and defects that are analyzed in this paper not only are they the source of the shell buckling phenomenon, but they are also the causes of the design and re-fitting of structural systems' improvement.

4. THEORETICAL ANALYSIS

The next section deals with the collection of works in the domain of theoretical research. The works closely connected with cylindrical shells are described as having the potential to deepen and clarify further ones understanding of cylindrical shells. The study on the static as well as dynamic behavior of laminated cylindrical shells developed the earlier knowledge of the critical loads decreasing factors, and it is of special importance because it also addresses such imperfections caused by the circular panels (see, for example, [4–9]). The study of geometric imperfection and the relevant knockdown factors (KDFs) has been one of the most demanding sectors in the field. It is a matter which is universally agreed on that the presence of flaws greatly affects the material's strength and its post-buckling behavior. To examine these effects through theory, numerous methods have been put forward, i.e., the Eigen mode shape approach, the method of perturbation loads, and the system of perturbation loads (SPLA). Theoretical results can be proven by testing in the lab (experiments) and in situ by using the same (Lee et al., No. 136). Nanyang Technological University. The instability nature and the behavior of cylindrical shell systems have been extensively explored. Research has been carried out in bending thin steel circular cylindrical shells as a tool for using electrocardiography (ECG) and checking the commercial viability of the external Fiber Reinforced Polymer (FRP) jackets in the case of steel columns. The paper also lists a variety of issues, where the various researchers have made contributions in the field of cylindrical shell mechanics.

Rephrased AcademicEnglish:

The delamination process and its effects in fiber composites has been a subject of research for a long time, and simulations have been used to address the physical problems that may result from this process. It is quite noteworthy that the only available reference is by Tafreshi (2002-2006) and is related to the experimental data of the delamination effect on buckling and post-buckling performance of composite cylinders under the combined effects of axial compression and lateral pressure [33–40]. The delamination of layered composites in aggressive environments caused by stress has been very well studied, while the influence of the combined actions is not completely clarified. The objectives of the present work are rooted in the requirement of a better understanding of

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the global performance of the composite cylinders against combined loading conditions and geometric imperfection. The prior sources dealt with the stability of laminated cylindrical shells with respect to different types of typical loadings, such as axial compression, pure external pressure, bending, and torsion and the loading, buckling, imperfection models, etc., are reported So in this paper and the corresponding reference should be looked up]. The modern history of cylindrical shell stability started after the work of Simitses (1967) who had studied orthotropic circular cylindrical shells under unilateral hydrostatic pressure and torsional loading [41]. The study line was further pursued by Arbocz (1974) that carried out an investigation of the influence of initial imperfections of thin shell structures. The foundations given by Anastasiadis and Simitses (1993) for the problem of the buckling of elongated, shear-deformable laminated cylindrical shells under pressure were further deepened by Anastasiadis et al. (1994) who made the subject of their research moderately thick shells [44]. In 1996, Huyan et al. [45] proposed a theoretical framework to analyze the nonlinear behavior of imperfect metallic and laminated cylinders subjected to bending. Their approach involved fabricating multiple scaled specimens, each tailored for testing either up to failure or just below failure thresholds. Building on this idea, Rezaeepazhand et al. (1996) developed scaled representations of symmetrically laminated cylindrical shells exposed to axial compression [46]. Earlier, Simitses et al. (1985) [47] initiated the quantification of imperfection sensitivity in laminated solid cylindrical shells under combined torsional and axial loads, marking a significant contribution to the field. Building on this work, Simitses (1986) [48] employed finite element methods to investigate and predict the most probable buckling modes. Then, the joint-products of Jaunky and Knight (1998, 1999) sought to further investigate the behavior of different structures in the event of buckling after the prior obtaining of their theoretical models' mode shapes [49–50]. Progress in research was still visible since Xue and Fatt (2002) continued the investigation of the stability problem in axially stressed non-uniform elongated cylindrical shells, incorporating the external static water pressure which is assumed hydrostatic, in their study (51). At an earlier date, finite element analysis (FEA) was used by Chaplin and Palazotto (1996) to determine the failure modes of sandwich composite cylindrical panels of different stiffness. The vertical cleavage of the sandwich right in the middle was also simulated in some research papers [52]. Hilburger and Starnes (2002, 2004) have dived into the influence of imperfections on the buckling load-carrying capacity of slenderness and compression loaded four-layer laminated composite shells [53–54]. Tafreshi (2002) conducted a notable study on the behavior of laminated composite cylindrical shells with notch holes subjected to internal pressure and axial loading [33]. Similarly, Shen (2001) investigated the post-buckling and compressive behavior of shear-deformable, cross-ply laminated composite cylindrical shells under the combined effects of external pressure and internal forces, with related topics explored in other works as well [55]. Adali et al. (2001) provided a detailed discussion on the design and fabrication of antisymmetric laminated shells exposed to both axial and external pressure loads [56], while Messager et al. (2002) focused on optimizing the slenderness design of such structures [57]. Winterstetter and Schmidt (2002) covered the issue of the stability of circular cylindrical steel shells, a topic which was related to the effect of various loads [17]. Nemeth et al. (2002) advanced research on the nonlinear behavior of the Space Shuttle's liquid-oxygen tank, focusing on the impact of imperfections that contributed to inaccurate initial conditions. Their study was extended by exploring the dynamics of super-light orbit structures [58]. Simultaneously, Xue and Fatt (2002) examined the effects of external hydrostatic pressure on the stability of thin-walled, non-uniform circular [51]. Featherston (2003) initiated studies on the effects of imperfections in curved panels, examining perfect compression-shear behavior and post-buckling responses [59]. This work laid the foundation for further research, including Wagner et al. (2020), who proposed new design approaches for thin-walled cylinders based on aeroelastic frequencies and paired geometric imperfections [61]. All the studies mentioned above indicate that the LPDT method (Lining Pulling Down and Turning around) has been the major research result for most thin-walled cylindrical shells, which eventually became the most mature and mainstream method for the present research as well.

The strength to depends on geometric imperfections [9]. Such defects can be classified into: realistic, worst-case and stimulable defects. Real structures with imperfections need non-contact measurement techniques for their evaluation, especially when Fourier series-based methods are used for their characterization and the consequences calculation. The natural development of imperfections such as LBMIs and ASI gives rise to many buckling phenomena, since optimization can easily create defective stiffened plates. In addition, the effect of geometrical imperfections on the KDFs is assessed and highlighted in the bibliography. In recent years, researchers have made efforts to improve the prediction accuracy of KDFs. The Single Perturbation Load Approach (SPLA) in particular has been shown to be a reliable approximation for real imperfection patterns. Surrogate models were established to enhance the efficiency of the WMPLA algorithms for the assessment of flaw sensitivity and the prediction of the KDF. Winterstetter and Schmidt (2004) classified geometrical defects [17]. The European standard (Eurocode 3, 1999) recommends to characterize imperfections in steel shells using the Eigen mode shapes [62], but this may result to be too conservative since the presence of these shapes can give rise to a reduction of the structure' axial stiffness even for small imperfection amplitudes. Hutchinson [63] observed that internal pressurization can reduce the imperfection sensitivity of cylindrical shells. Additionally, the study reported that for loadings characterized by lower-magnitude circumferential membrane stress components, the imperfection sensitivity decreased. This trend was examined for both cylindrical and spherical shells with varying K values, highlighting the influence of low transverse membrane stress components [64]. To attenuate the sensitivity of axially loaded cylindrical shells to imperfections, Pellegrino NING and (2015, 2017) suggested a wavy shell design approach. Although optimization tools may detect some of the most crucial imperfections (Lund, 2010 and Deml, 1997; Lindgaard), it is unclear whether these imperfections are accurately represented [67-68]. They exhibit unique buckling behavior with the introduction of individual imperfections like LBMIs and ASI. To conduct detailed buckling analyses, the NASA Shell Buckling Knockdown Factor Project integrates geometric imperfections identified through optical metrology into numerical models, utilizing cutting-edge methods such as 3D digital image correlation (DIC) [16, 69–72]. The efficiency of the assessed imperfections has been verified proving the good prediction capability of the buckling stresses of both composite unstiffened and stiffened shells [73-74]. Following buckling investigations in both sub-scale [41] and full-scale [42-43] cylinders, this approach has been validated, with errors on the order of 1.5% of experimental test loads. Hühne et al. (2008) proposed an alternative method, the single perturbation load approach (SPLA), for manufacturing realistic dimple-shaped imperfections [78]. It demonstrates a good correspondence to real imperfections, and can predict knockdown factors with uncertainty [79, 80]. Castro et al. (2014) among other methods, corroborating the direct predictions of the knockdown-factors as determined with SPLA [74]. Wagner et al. (2017) formulated perturbation techniques for the analysis of both cylindrical and conical shells, enabling the forward prediction of lower-bound buckling stresses in the absence of explicit imperfection descriptions [81-82]. Hess (1961), Cheng and Ho (1963), and, more recently, Lennon and Das (2000) studied different buckling phenomena with the finite element approach 83. The shear capacity of concrete-filled FRP composite circular tubes was investigated by Burgueño and Bhide (2006) [85] and the analysis of the non-classical mode of buckling was reported by Paimushin (2007) [86]. It was also found by Tafreshi and Bailey [2007] that the buckling behavior of composite cylindrical shells, subjected to combined loading, was significantly influenced by initial imperfections [40]. Li and Shen (2008) analyzed the post-buckling performance of thermal–loaded three-dimensional braided composite cylindrical shells [86], and the dynamic response of multilayered FRP cylindrical shells was reported in Pavlou (2016) [87]. Phuong et al. (2019) studied the nonlinear stability of sandwich functionally graded cylindrical shells [88], while Scarselli, Luciano, et al. (2020) also, presented design tools for imperfection-sensitive shells subjected to axial loading with experimental verification [89].

Previous strategies considered precise numerical testing models, which were confirmed by real data. Those very experiments had already been referred to in a paper about the behavior of the shells with a lot of different loadings and the differences between the results obtained from the experiments were calculated. Measured defect analysis has proven highly effective for predicting the buckling stress of composite shells, although conventional boundary conditions often limit analytical precision. To overcome this, advanced methods such as the perturbation and artificial spring techniques have been developed. Building on these advancements, Wang et al. (2014) introduced further improvements, while Gupta et al. [90–91] proposed the Worst Multiple Perturbation Load Approach (WMPLA), aiming to refine knockdown factor (KT) calculations. This approach strategically distributes under configured dimple-shaped imperfections across the shell surface and utilizes optimization algorithms to determine their best configuration. The effectiveness of WMPLA was confirmed through a full-scale buckling experiment conducted on a 4.5-meter diameter reinforced shell subjected to axial compression with various potential imperfections [92]. Its successful application demonstrated WMPLA's ability to predict KD factors reliably during the preliminary design stage. The computation requirement of optimizing thick-walled stiffened shells is still large; therefore the authors introduced a surrogate model into the optimization process, in order to alleviate the

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computational load of WMPLA [93–96]. A Fourier series method was employed to predict the influence of various geometric imperfections, revealing that longer-wavelength modes offer greater stability, while axisymmetric imperfections significantly lower buckling loads. However, applying the WMPLA method can be labor-intensive, particularly in the case of stiffened cylindrical shells [88] and conical shells [97]. It is indispensable that buckling investigation be conducted for understanding the behavior of cylinder shell, namely the buckling behavior and post-buckling behavior in thin CFRP cylinder shell. An in-depth investigation examined the quasi-static and dynamic axial compression responses of composite materials subjected to both load-controlled and displacement-controlled loading [98]. The developed approach correlates material and geometric characteristics within finite element models, providing a physical interpretation of buckling behavior in thin-walled composite cylinders. Dynamic testing, performed alongside static compression tests on thin-walled composite tubes load was approximately 5% greater than the static buckling load [99]. This result, however, was perhaps due to the combination of the dynamical and statical aspects of the test. For the numerical model to be trustworthy, the static and dynamic buckling stresses and the damping coefficients of the composite structures must be partially or fully obtained. Khakimova et al. (2016) axially crushed CFRP cones with both unloaded and unstiffened DLR at DLR [100]. As detailed in the studies below [101–102], both theoretical and experimental investigations have confirmed that conventional and unconventional initial imperfections significantly impact the buckling load of composite shells. Common imperfections include deviations in the middle surface, while non-typical defects involve variations in shell wall thickness, gaps between local layers caused by manufacturing processes, geometric discontinuities at shell edges, uneven end loading, or changes in boundary conditions. Tall et al. (2018) analyzed elastoplastic buckling and collapse of spherical shells subjected to in-plane loads and identified the key parameters in buckling capacity curves and the influence of imperfections on that [5]. In 2019, Fan introduced a non-invasive probing technique to estimate the critical buckling stress of axially loaded cylinders. The study acknowledged that the probe's positioning had a significant impact on prediction accuracy, especially for shells with localized damage [103]. Collectively, these investigations have advanced the understanding of shell behavior under various loading conditions, contributing to the development of more refined design strategies. Building on this work, Yadav and Gerasimidis (2019) examined the buckling performance and imperfection tolerance of slender, thin-walled steel cylinders used in the energy sector. Their study also assessed the critical buckling load, incorporating the effects of steel strain-hardening and bending behavior models [104].

A number of studies have investigated the use of FRP wrapping in different applications, in particular for its ability for improving buckling behavior. Literature review In this work, existing literature is reviewed to put shell behavior under multiracial loading conditions into context. Their research emphasized identifying the most critical stages of loading and examining the influence of the steel strain hardening model on the bending response, with particular attention to slenderness ratios, which are highly relevant to applications in the energy sector. The results are quite enlightening in terms of the new design techniques development for imperfect structures [104].

Krishna et al. (2021) conducted an investigation adding to the result of the research study that was carried out in an earlier phase to estimate that the application of the external FRP composite wrapping that contributes significantly to the buckling load of metallic cylindrical shells. Their numerical study was the basis for the formation of new buckling modes and the plotting of the graphical description of the buckling behavior of various metallic shells with their geometric ratios having been varied by means of different forms, and widths of FRP reinforcements. The data are informative about the fact that the shell's strength in an elastic state grew in direct proportion to the net hoop modulus of the FRP material. Conversely, shells that underwent plastic post-buckling displayed asymmetric deformation patterns. The necessary stiffness reduction induced by the FRP wrapping to achieve yielding was closely associated with the emergence of less symmetrical shell configurations, reflecting the interconnected aspects of their structural response. Further, the increase of the longitudinal stiffness of FRP led to large yielding capacity and the pre-strain localization stiffness and, at the same time, obtained the maximum buckling load by the plastic shells; i.e.a great deformation in the elastic stage was responsible for the largest value of the buckling load. Sofiyev and Hui (2019) made a much deeper investigation concentrating on the stability, vibration and FGM cylindrical shells which they obtained obtained through the employment of the first-order theory of the shear ratio and analyzed the effect of the Galerkin method and thus gave an idea of the first steps the authors had done in the development of the obtained results. Their research utilized the method of the singular value problem analysis to

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extract the critical values from the testing activity in several key parts and mixed it with numerical data that supports the analytical validation of the model in the paper. The study was extended to investigate the sole influence of volume fraction changes, functionally graded material compositions, and different shell geometries on eigenvalue behavior [105].

This research realm is focused on understanding and introducing a method of in-plane buckling resistance improvement with the use of recyclable Fiber Reinforced Polymer (FRP) wrapping of geotechnical structures. Knowledge of the classification of shells is inevitable for the mechanical behavior of the shells under various types of loading and consequently leads to the design criteria of different structural systems being improved. Allahbakhsh and Shariati (2014) handled the problem of buckling instability caused by cracks in composite hollow cylinders when loaded together. They explained that the axial cracks are the major failure mode, which reduces the buckle load significantly [106]. The study on the dynamic axial stresses and hydrothermal influences on the resonance of a rotating composite laminated shallow cylindrical shell was conducted by Li (2021) in another work [107]. The research of Liu et al. (2021) investigated the highly complex forced vibrations of constrained non-linear piezoelectric cylindrical shells subjected to electro-thermo-mechanical loading with the effect of micro-voids [108]. These studies significantly contribute to understanding the behavior of cylindrical shells under various stress conditions and offer valuable insights for optimizing their design. However, certain aspects of the response of cylindrical shell assemblies to different environmental conditions remain unclear. To address this, the authors developed an experimental setup and, through the application of an artificial spring, identified the general boundary conditions necessary for deriving the equations of motion, as well as for analyzing free and forced vibrations. They also researched the process of applying dynamic load to a material with different covering patterns, different boundary conditions, and different coating thickness. In another related study, the authors consider the elastoplastic analysis of FGM cylindrical shells in various stress states [109]. Sofiyev and Hui developed a new way of deriving a closed-form solution for eigenvalue problems in mixed boundary condition, and Li et al. wrote a paper giving a complete and unified vibration model along with an artificial spring method for any boundary conditions.

5. FUTURE RESEARCH DIRECTIONS

Although extensive research has been conducted on the buckling behavior of FRP-reinforced cylindrical shells, certain questions remain unresolved, particularly regarding the mechanisms by which FRP suppresses different buckling modes. Gaining a comprehensive understanding of the research landscape requires adopting a perspective that goes beyond a single, one-sided view. This involves making breakthroughs between the experimental and theoretical domains, that way, a more dynamic view of the behavior of cylindrical shells can be given. As well as the most urgent needs, the research should also try to take care of the long-term performance and durability of various infrastructures, keeping in mind the aspects of aging, cyclic loading, and environmental effects. The imperfections effect on retrofitting, notably, the FRP jackets' efficiency is the main drive for further study. With the current availability of just a little amount of literature on the interaction of different loading conditions, it is pointed out that a very detailed investigation involving, for example, simultaneous external/internal pressure and bending moments, is needed. Research that has been done earlier thus had been following a pattern of problem-solving of KDF quantifying/estimation by minimizing KDF perturbation with respect to a particular loading condition, imperfection and/or buckling modes forming the basis for a predefined loading parameter. However, the various studies employed different imperfection methodologies, and yet, they faced challenges in the proper modeling of the worst imperfections and in the spreading of the necessary imperfections. Some methodologies such as WMPLA belong to such a category of emergent practices which have that potential but caution and carefulness need to be brought into the practical part. The process of making the model as close to the reality as possible would necessarily require the utilization of experimental validation, especially in a dynamic setting. In conclusion, an alternative of buckling performance improvement with the addition of FRP layers to the external of the shells offers up that there can indeed be new paths for design methodologies, for which it now should be noted as future research on this subject can properly seek the advantages offered by FRP in a variety of shells under different loading conditions.

The potential way to go for Fiber Reinforced Polymer cylindrical shells under combined Torsion and External Pressure loading is to experiment with different types of fiber-reinforced polymers and observe their influence on

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

the imperfection sensitivity of cylindrical shells. This is achieved by conducting extensive experiments on the behavior of the shell under various temperatures, environmental conditions, and loading scenarios. Besides, the development of the design methodologies that involve the incorporation of measured imperfections/ and design under extreme-case scenarios is the most trusted and likely way that the overall safety/reliability of cylindrical shell structures will be improved. The next phase of the research should focus on the conjugation of loading rates with the sensitivity of a cylindrical shell to imperfections and the subsequent post-buckling behavior of the shell. This can be achieved by varying the loading condition (mixture of loading rates) and considering a variety of cylindrical shells from fixed to simply supported ends. Another topic that would be tackled in the future deals with the coming up of methods of optimization that can scrutinize the problem of worst-case imperfections for cylindrical shells under combined loading conditions. The additional studies that can be added to the list of related studies and be focused on are, for example, how different shapes and sizes of defects would affect the response of cylinders under combined loading. Moreover, the expansion of the research in the area of geometries with other forms of shells, such as conical, and spherical shells, possibly insights into the behavior of cylindrical structures. Accordingly, the identification and the usage of the above-mentioned progressive flows of research in the field will lead to a closer to complete grasping understanding of the behavior of Fiber Reinforcement Polymer cylindrical shells with the effect of simultaneous torsion and external pressure loading, improving the design, safety and reliability of the reinforced structures.

6. CONCLUSION

So all in all the current study presents a comprehensive overview of the research which conducted on cylindrical shells subjected to different loadings. Research cover from the 1960s to now, clustered over time suggests growing interest. Studies covering materials such as CFRP composites, FRP, steel, and functionally graded materials have underscored the significant influence of material properties on shell behavior. The considered loading scenarios range from axial compression and torsion to external pressure and their combinations, with the combined axial compression and external pressure scenario emerging as a key area of focus in recent research. Experimental studies, theoretical modeling, and literature reviews form the core research approaches. Building on previous papers, Laboure's work emphasizes experimental validation, supported by computer modeling and simulation, where numerical validation and simulation processes play a central role. Across various studies, it has been emphasized that the nonlinear response of rings is heavily influenced by initial geometric imperfections, with particular attention given to their effects on cylindrical shell structures. Research into thin-walled aluminum shells of revolution has highlighted the critical impact of geometrical deviations on buckling performance, stability, and structural capacity. In recent years, studies have increasingly concentrated on imperfection sensitivity, especially regarding the load-carrying capability of thin-walled cylindrical shells. To capture realistic and extreme imperfections, researchers have adopted a variety of numerical and mathematical simulation approaches. Thus, eventually leading to the prospective research pathway for Fiber Reinforced Polymer (FRP) cylinders and columns under the combined loading condition of Torsion and External Pressure focusing on the effect of various FRP materials on the imperfection sensitivity of the cylinders. This represents systematic study of shell behavior under different temperature and environmental conditions with combined loading. New design methods that incorporate prescribed imperfections and extreme-case scenarios provide a strong foundation and further potential for safety and reliability improvements of cylindrical shell structures. Broaden such exploration, interrogating modulation of load rate, sensitivity to imperfections, and any nuanced responses to variations of Extreme Boundaries, from Fixed to Simply Supported ends would prove insightful. Another hopeful avenue is the advancement of optimization methods to correctly pinpoint worst-case imperfections for homogenous cylindrical shells under combination of loading conditions. Furthermore, examining the influence of different imperfection shapes and sizes, as well as broadening studies to include other geometries such as conical or spherical forms, could greatly complement our understanding of the behavior of cylindrical shells. Combined torsion and external pressure loading conditions are critical stress scenarios that FRP cylindrical shells may encounter in multiple applications; hence, research on this topic will help facilitate comprehensive understanding and enrich design methodologies for these structural components while ensuring their safety and performance. Top of Form. To summarize this review, table 1 is provided.

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

Table 1 summary of the reviewed papers

Number	Author name	year of publicatio n	Material (s) used in the cylindrical shell	Loading condition (s)	Method (s)	Key findings
1	Abramovich	2002	NA (Not specified)	Combined loading (type not specified)	Experimenta l	Repeated buckling influences the geometric flaws in strong cylindrical shells under combined loading conditions.
2	Adali	2001	NA (Not specified)	Axial load and external pressure	Theoretical	Design of multilayer shells for minimum sensitivity under axial stress and external pressure.
3	Allahbakhsh	2014	CFRP composite	Combined loading (type not specified)	Experimenta l	Instability to damaged CFRP composites cylindrical shells submitted to combined loading conditions.
4	Anastasiadis	1993	NA (Not specified)	Axial compression and torsion	Theoretical	Instability of pressure-loaded, elongated, Shear-deformable cylindrical laminate the shells.
5	Anastasiadis	1994	NA (Not specified)	Combined compression (axial compression)	Experimenta l	Fouling of fairly wet, thick, tubular shells from simultaneous internal pressure and axial loading are the main causes of the system's instability.
6	Arbelo	2014	NA (Not specified)	NA (Not specified)	Theoretical	Quantitative analysis of composite structures responsive to imperfections.
7	Arbocz	1974	NA (Not specified)	NA (Not specified)	Theoretical	The impact of initial defects on the stability of thin-shell structures.
8	Barthelemy	1993	NA (Not specified)	NA (Not specified)	Theoretical	Approximation methodologies for optimal structural design.
9	Batikha	2008	FRP composites	NA (Not specified)	Experimenta l	Fiber-reinforced composites of polymers augment the buckling strength of defective cylindrical shells.
10	Batikha	2009	FRP	Axial compression	Experimenta l	Reinforcing steel cylindrical shells to avert elephant's foot buckling with the application of FRP.
11	Bisagni	2015	NA (Not specified)	Axial loading (dynamic and static)	Experimenta l	An experimental investigation on composite cylindrical shells under

						static and cyclic axial loading.
12	Bisagni	2003	CFRP	Combined axial and torsion loading	Experimenta l	This study explored the failure progression and after-failure response of CFRP cylindrical shells under combined axial and torsional loading conditions.
13	Burgueño	2006	Concrete-filled FRP composite	NA (Not specified)	Experimenta l	Shear properties of cylindrical shells composed of concrete-filled FRP composites.
14	Calladine	1988	NA (Not specified)	NA (Not specified)	Theoretical	The concept of thin shell constructions from 1888 to 1988.
15	Castro	2014	NA (Not specified)	Axial compression	Theoretical	Associated research on low-order models employing geometrical imperfections to obtain a parametric knock-down function for Composite cylindrical shells under axial compression.
16	Chaplin	1996	NA (Not specified)	NA (Not specified)	Theoretical	Thickness variation of cylindrical panels were used for the analysis and determination of the results.
17	Chaudhuri	2014	NA (Not specified)	NA (Not specified)	Experimenta l	Efficient global optimization using adaptive target formulation.
18	Cheng	1963	NA (Not specified)	Combined torsion and hydrostatic pressure	Theoretical	Stability of heterogeneous anisotropic cylindrical shells subjected to coupled loading.
19	Das	2014	FRP	NA (Not specified)	Experimenta l	Application of fiber-reinforced polymer composites (FRP) in civil engineering.
20	Deml	1997	NA (Not specified)	NA (Not specified)	Theoretical	Direct evaluation of the most deleterious defect morphology in shell buckling.
21	Ekstrom	1963	NA (Not specified)	Combined torsion and axial compression	Experimenta l	Instability of cylindrical shells under concurrent torsion and hydrostatic pressure.
22	EN	1993	Steel	NA (Not specified)	Theoretical	Euro code 3: Structural design of steel frameworks. Standards and directives for

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

						edifices.
23	Fan	2019	NA (Not specified)	Axial compression	Theoretical	Forecasting critical buckling stress for axially compressed cylindrical shells via a non-destructive testing method.
24	Fatemi	2013	NA (Not specified)	Uniform external pressure	Experimental	Examinations of defective cylindrical shells under uniform external pressure.
25	Featherston	2003	NA (Not specified)	Combined compression	Theoretical	Reactivity to flaws in curved panels exposed to simultaneous compression and shear forces.
26	Frano	2009	NA (Not specified)	Uniform external pressure	Experimental	Imperfections alter the buckling properties of slender cylindrical shells subjected to uniform external pressure.
27	Gardner	2018	NA (Not specified)	NA (Not specified)	Theoretical	Digital image correlation augments test data evaluation and refines structural simulations.
28	Ghazijahani	2013	NA (Not specified)	Pure bending and external pressure	Experimental	Experiments on cylindrical shells demonstrate their behavior under pure bending and external pressure.
29	Hao	2016	NA (Not specified)	NA (Not specified)	Theoretical	The equivalent multiple perturbation load method results in a design of stiffened conical shells that is insensitive to imperfections.
30	Hao	2015	NA (Not specified)	NA (Not specified)	Experimental	Reliability-based design optimization for imperfect stiffened shells is supported by the hybrid framework.
31	Hao	2014	NA (Not specified)	NA (Not specified)	Theoretical	Hybrid optimization methodology for hierarchical stiffened shells employing the smeared stiffener technique and finite element analysis.
32	Hao	2013	NA (Not specified)	NA (Not specified)	Theoretical	Surrogate-based optimization was used to assess the load-carrying capacity and the vulnerability of stiffened shells to defects.
33	Hao	2016	NA (Not	NA (Not	Theoretical	The optimization of

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

			specified)	specified)		curvilinearly stiffened panels with a single cutout considers the collapse load.
34	Hao	2017	NA (Not specified)	NA (Not specified)	Experimenta l	Non-probabilistic reliability-based design optimization approach employing the enhanced chaos control method.
35	Hao	2018	NA (Not specified)	NA (Not specified)	Experimenta l	Comprehensive framework incorporating precise modeling, isogeometric analysis, and optimization for variable-stiffness composite panels.
36	Haynie	2010	NA (Not specified)	Axial compression	Experimenta l	Different ways of calculating the minimum buckling load of cylinders subjected to axial pressure.
37	Hess	1961	NA (Not specified)	Combined loading	Experimenta l	Stability assessment of orthotropic cylindrical shells subjected to coupled loading.
38	Hilburger	2008	FRP	NA (Not specified)	Experimenta l	Design requirements for shell buckling predicated on initial defect profiles.
39	Hilburger	2018	NA (Not specified)	NA (Not specified)	Theoretical	Establishing buckling reduction coefficients for reinforced metallic launch vehicle cylindrical shells.
40	Hilburger	2002	NA (Not specified)	NA (Not specified)	Theoretical	Imperfections substantially influence the buckling behavior of compression-loaded composite shells.
41	Hilburger	2004	NA (Not specified)	NA (Not specified)	Theoretical	Impact of defects on the buckling behavior of composite shells.
42	Hilburger	2006	NA (Not specified)	NA (Not specified)	Experimenta l	Design criteria for shell buckling based on manufacturing defect signatures.
43	Hornung	2002	NA (Not specified)	imperfections	Theoretical	Critical loads of tank shells exhibiting flaws.
44	Hu	2020	FRP	NA (Not specified)	Experimenta l	A review of experimental investigations on the application of FRP for the reinforcement of bridge constructions.
45	Hühne	2008	NA (Not specified)	axial compression	Theoretical	A full procedural framework encompassing the design, evaluation, and verification

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

						of composite cylindrical shells under axial compression was established.
46	Hutchinson	1965	NA (Not specified)	Axial buckling of pressurized imperfect	Experimental	Buckling of compressed cylindrical shells with initial imperfections.
47	Hutchinson	2010	NA (Not specified)	reduced biaxial membrane stress	Theoretical	Critical parameters for the buckling of cylindrical and spherical shells subjected to diminished biaxial membrane stress.
48	Huyan	1996	NA (Not specified)	bending loads	Experimental	Nonlinear study of flawed metallic and laminated cylinders subjected to bending loads.
49	Jasion	2009	NA (Not specified)	under external pressure	Theoretical	Equations of stability for slender elastic barrel-shaped shells subjected to external pressure.
50	Jaunky	1999	NA (Not specified)	axial compression	Experimental	Evaluation of shell theories for the buckling circular cylindrical laminated composite panels subjected to axial compression.
51	Jaunky	1998	NA (Not specified)	NA (Not specified)	Theoretical	Buckling analysis of curved panels and shells made of anisotropic materials.
52	Kaneko	2008	FRP	Impact forces applied transversely	Theoretical	Finite element method failure analysis of a pressurized FRP cylinder under transverse impact loading.
53	Kepple	2015	NA (Not specified)	NA (Not specified)	Theoretical	Realistic imperfection models applied to the stochastic analysis of imperfection-sensitive unstiffened composite cylinders.
54	Khakimova	2016	CFRP	Axially compressed CFRP truncated cones	Experimental	The buckling behavior of axially compressed CFRP truncated cones was examined using both experimental and numerical approaches.
55	Khamlichi	2004	NA (Not specified)	NA (Not specified)	Theoretical	The effect of localized axisymmetric imperfections on the stability of elastic cylindrical shells was

						investigated.
56	Krishna	2021	FRP	NA (Not specified)	Experimenta l	FRP strengthening effectively improves the buckling characteristics of metallic cylindrical shells.
57	Lennon	2000	NA (Not specified)	Combined loading	Experimenta l	Torsional buckling behavior of stiffened cylinders under combined loading.
58	Li	2021	NA (Not specified)	Arbitrary boundary conditions	Theoretical	Unified vibration modeling and dynamic analysis of FRP-FGPGP cylindrical shells under arbitrary boundary conditions.
59	Li	2021	NA (Not specified)	Periodic axial loads and hygrothermal environment	Theoretical	Parametric resonances of rotating composite laminated nonlinear cylindrical shells under periodic axial loads and hygrothermal environment.
60	Li	2008	3D braided composite	Axial compression in thermal environments and combined external pressure	Theoretical	3D braided composite cylindrical shells frequently encounter post-buckling under simultaneous pressure and axial loads in practical applications, and environmental temperature shifts can worsen the degradation of both the matrix and fiber materials.
61	Li	2022	Composite laminated	Underwater environment	Theoretical	Buckling prediction for composite laminated cylindrical shells in an underwater environment.
62	Lindgaard	2010	Composite	NA (Not specified)	Theoretical	Nonlinear buckling optimization of composite structures.
63	Liu	2021	NA (Not specified)	Electric-thermo-mechanical loads	Theoretical	Nonlinear forced vibrations of functionally graded piezoelectric cylindrical shells under electric-thermo-mechanical loads.
64	Lovejoy	2010	NA (Not specified)	NA (Not specified)	Theoretical	The structural design of stiffened cylinders is influenced by panel slenderness, internal pressure specifications, and material selection.
65	Maali	2012	NA (Not specified)	Weld-induced imperfections	Experimenta l	The objective of the study was to examine the impact of welding imperfections on

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

						the external load-induced buckling of conical shells.
66	Meng	2015	NA (Not specified)	NA (Not specified)	Theoretical	Design optimization of stiffened shells under buckling constraints using a non-probabilistic reliability approach.
67	Messager	2002	NA (Not specified)	NA (Not specified)	Theoretical	Best lamination of a narrow, underwater, composite cylindrical vessel.
68	Meyer-Piening	2001	CFRP composite	Combined axial and torsion loading	Experimental	This article presents an investigation of buckling loads of CFRP composite cylinders under combined axial and torsion loading. The investigation is carried out through both computational and experimental methods.
69	Nemeth	2002	NA (Not specified)	NA (Not specified)	Experimental	Nonlinear Behavior of the Liquid-Oxygen Tank in a Lightweight Space Shuttle: The Role of Initial Geometric Imperfections.
70	Neşer	2017	Polymer-based composites	NA (Not specified)	Review	An overview of the evolution of polymer-based composites in marine applications and their potential future developments.
71	Ning	2015	NA (Not specified)	NA (Not specified)	Theoretical	Imperfection-insensitive axially loaded thin cylindrical shells.
72	Ning	2017	NA (Not specified)	NA (Not specified)	Experimental	Research on axially loaded cylindrical shells with reduced sensitivity to imperfections.
73	Opoka	2009	NA (Not specified)	axially compressed	Theoretical	Further investigation was carried out on the bifurcation buckling behavior of axially compressed circular cylinders.
74	Orifici	2013	Composite	Compression	Theoretical	Analysis of imperfection induced by a disturbance in compression buckling of cylindrical shells.
75	Paimushin	2007	NA (Not specified)	Combined loading (torsional,	Theoretical	The combined load effect on the cylindrical shell is described through its

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

				flexural, and torsional-flexural buckling modes)		buckling modes of torsional, bending, and torsional-flexural in this article.
76	Pavlou	2016	FRP (Fiber-Reinforced Polymer)	Unsteady loading conditions	Experimental	Unsteady load effects on the dynamic response of multi-layered FPR cylindrical shells.
77	Phuong	2019	Sandwich functionally graded material	Axial compression in thermal environment	Theoretical	Nonlinear stability of sandwich functionally graded cylindrical shells with stiffeners under axial compression in thermal environment.
78	Priyadarsini	2012	Advanced fiber composite	Axial compression	Theoretical	Advanced fiber composite cylinders subjected to axial compression were analyzed for buckling behavior through both numerical and experimental investigations.
79	Ramadan	2010	FRP (Fiber-Reinforced Polymer) composites	Effect of FRP composites on buckling capacity	Experimental	Effect of FRP composites on the buckling capacity of anchored steel tanks.
80	Rezaeepazhand	1996	NA (Not specified)	Axial compression	Theoretical	Reduced size models of laminates, that bear axial loading, in order to produce cylindrical shells.
81	Ross	2005	NA (Not specified)	Hydrostatic pressure applied externally.	Theoretical	Ring-stiffened conical shells experiencing plastic buckling under external hydrostatic loading.
82	Rudd	2018	Metallic	NA (Not specified)	Experimental	Deformation behavior of a huge, smooth, orthogrid-stiffened metal cylinder subjected to compression load.
83	Schmidt	2000	Steel	NA (Not specified)	Theoretical	Stability of steel shell structures: General Report.
84	Schneider	0	NA (Not specified)	Uniform external pressure	Theoretical	Regular equivalent geometrical distortions provide an effective quantitative approach for evaluating the buckling load.
85	Schultz	2012	CFRP (Carbon Fiber Reinforced	NA (Not specified)	Experimental	Compression response of fluted-core composite panels.

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

			Polymer) composites			
86	Schultz	2018	Composite	NA (Not specified)	Experimenta l	Experiment and investigation of a buckling-dominated huge sandwich composite cylinder.
87	Shen	2001	NA (Not specified)	Effect of combined external pressure and axial compression.	Theoretical	Shear-deformable cross-ply laminated cylindrical shells experiencing post-buckling under the combined action of external pressure and axial compressive loads.
88	Showkati	1996	Shallow cylindrical shells	Primary boundary conditions	Experimenta l	Influence of primary boundary conditions on the buckling of a flat cylindrical shell.
89	Silvestre	2008	NA (Not specified)	Compression	Theoretical	Compression induced buckling in elliptical cylindrical tubes and shells.
90	Simitses	1967	Orthotropic	Combined torsion and hydrostatic pressure	Theoretical	Instability of orthotropic cylindrical shells under combined torsion and hydrostatic pressure.
91	Simitses	1986	NA (Not specified)	NA (Not specified)	Theoretical	An Overview of Buckling and Post-Buckling Behavior in Imperfect Cylindrical Shells.
92	Simitses	1985	NA (Not specified)	Torsion and axial compression	Theoretical	Analysis of imperfection sensitivity in laminated cylindrical shells under torsion and axial compression.
93	Sofiyev	2019	FGM (Functionall y Graded Material)	External pressures with mixed boundary conditions	Experimenta l	The dynamic response and instability of cylindrical FGM shells under external loading and mixed boundary conditions are analyzed.
94	Sosa	2006	FRP (Fiber-Reinforced Polymer)	NA (Not specified)	Theoretical	General-purpose finite element codes are applied to calculate the lower-bound elastic buckling loads of structures.
95	Tafreshi	2002	Composite	axial compression loads and Internal pressure	Theoretical	An examination is conducted post-buckling behavior of composite cylindrical and buckling with cutouts subjected to internal pressure and axial compression.

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

96	Tafreshi	2002	Composite	NA (Not specified)	Theoretical	Using the Boundary Element Method for Shape Optimization of Two-Dimensional Anisotropic Structures.
97	Tafreshi	2003	NA (Not specified)	Shape design sensitivity analysis	Theoretical	Shape optimization of two-dimensional anisotropic structures using the boundary element method.
98	Tafreshi	2004	Composite	external pressure	Theoretical	Delamination buckling and postbuckling in composite cylindrical shells under external pressure.
99	Tafreshi	2004	Composite	axial compression	Theoretical	Efficient modeling of delamination buckling in composite cylindrical shells under axial compression.
100	Tafreshi	2005	Composite	NA (Not specified)	Theoretical	Optimum shape design of composite structures using the boundary element method.
101	Tafreshi	2006	Composite	Combined axial compression and external pressure	Theoretical	Delamination-induced post-buckling and buckling responses of composite cylindrical and external pressure loading.
102	Tafreshi	2008	Composite	NA (Not specified)	Theoretical	Delamination buckling of composite cylindrical shells.
103	Tafreshi	2007	Composite	Combined loading (Imperfect)	Theoretical	Composite cylindrical shells with imperfections subjected to combined loads present an instability issue that continues to be controversial.
104	Tall	2018	Composite	Combined loadings (Elastoplastic)	Theoretical	Regular bending and destruction of the domed shells were done to check the loadings from various sides.
105	Teng	2007	Cylindrical shells and circular steel tubes strengthened with FRP jackets.	Axial compression	Experimental	Performance of steel tubes and cylindrical shells reinforced with FRP under axial loading.
106	Teng	2001	Steel silo transition junctions	Buckling experiments	Experimental	Techniques for buckling experiments on steel silo transition junctions.
107	Tennyson	1969	NA (Not	Axial	Experimenta	Buckling of an axially

Journal of Information Systems Engineering and Management
2025, 10(41s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

			specified)	compression	l	symmetric imperfect circular cylindrical shells under axial compression.
10 8	Tian	2018	Stiffened shells	NA (Not specified)	Theoretical	A high-fidelity approximate model for determining lower-bound buckling loads for stiffened shells.
10 9	Vakili	2016	FRP (Fiber-Reinforced Polymer)	Elephant foot buckling and retrofitting of cylindrical shells by FRP	Experimenta l	Experimental and numerical investigation of elephant foot buckling and retrofitting of cylindrical shells by FRP.
110	Wagner	2020	NA (Not specified)	Axial compression	Theoretical	Minimum design criteria for deterministic and probabilistic cylindrical shells subjected to axial compression.
111	Wagner	2017	Cylindrical and conical composite shells	NA (Not specified)	Theoretical	Designing and investigating knockdown factors that are resilient to a load for the setup of axial loaded laminate shells of cylinders and cones.
112	Wagner	2017	NA (Not specified)	NA (Not specified)	Theoretical	Resilient design requirements for axially loaded cylindrical shells - research and confirmation.
113	Wagner	2020	NA (Not specified)	Axial compression with loading imperfections	Experimenta l	Examination of cylindrical shell buckling subjected to axial compression with loading imperfections: An experimental and numerical analysis of low knockdown factors.
114	Wang	2019	NA (Not specified)	Axial compression	Experimenta l	Experimental verification of cylindrical shells subjected to axial compression for enhanced knockdown factors.
115	Wang	2016	Stiffened shells	Axial compression	Theoretical and Experimenta l	Knockdowns factors for strengthened shells under axial compression, determined using experimental and numerical approaches.
116	Wang	2013	NA (Not specified)	Buckling with surrogate model	Theoretical	Assessment of the most plausible worst defect for cylindrical shells utilizing a surrogate model.
117	Wang	2014	NA (Not	Axial	Theoretical	Optimization of the

2025, 10(41s)
e-ISSN: 2468-4376
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			specified)	compression		dimensional arrangement in two phases for axially compressed stiffened panels.
118	Wang	2018	Quasi-perfect cylindrical shell	Axial compression	Experimenta l and Theoretical	Investigation of buckling in quasi-perfect cylindrical shells subjected to axial compression by experimental and computational methods.
119	Winterstetter	2002	Circular-section cylindrical steel shells.	Combined loading	Theoretical	Stability of circular cylindrical steel shells subjected to coupled loading.
120	Xue	2002	Circular cylindrical steel shells	External hydrostatic pressure	Theoretical	Instability of a nonuniform, long cylindrical shell exposed to external hydrostatic pressure.
121	Yadav	2019	Steel	Bending	Experimenta l	Instability for steel cylindrical shells under bending.
122	Yamada	1999	NA (Not specified)	Axial compression	Theoretical	Insights for the behaviors of axially compressed cylinders.
123	Yan	2019	Shell structures (not specified)	BESO algorithm form-finding method	Theoretical	A novel form-finding technique for shell structures utilizing the BESO algorithm.
124	Ziemian	2010	Metal structures (not specified)	NA (Not specified)	Theoretical	Guidelines for stability design standards for metallic constructions.

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