BUCKLING AND POST-BUCKLING OF ISOTROPIC AND COMPOSITE STIFFENED PANELS: A REVIEW ON ANALYSIS AND EXPERIMENT (2000-2012)

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SUMMARY

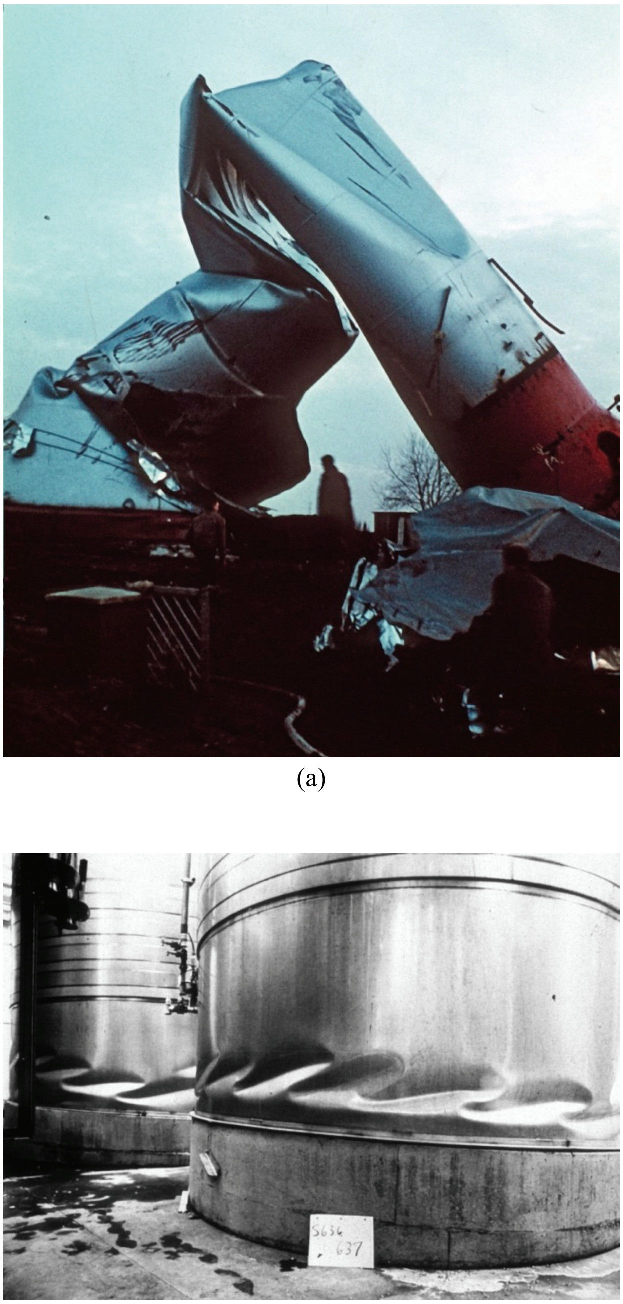
Stiffened panels made out of isotropic or anisotropic materials are being extensively used as structural elements for aircraft, maritime, and other structures. In order to maintain stiffness and strength with light weight, new design techniques must be employed when utilising these materials. Their stability, ultimate strength and loading capacity are the key issues pertaining to these engineering structures which have attracted a number of investigators to undertake in-depth research, either in an academic or actual engineering context. This paper provides an extensive review of the research which has been conducted in recent years (2000-2012) on the buckling and post-buckling response of isotropic and composite stiffened plate and shell structures related to analysis and experiment. The key objective of this review article is to collate the research performed in the area of buckling and post-buckling behaviour of stiffened structures, thereby giving a broad perspective of the state-of-the-art in this field.

1. INTRODUCTION

New, fast, large, efficient and safe aerospace, marine and civil engineering structures, among others, require the adoption of new structural concepts and materials with superior mechanical performance. However, it is in the area of marine structures that this is most highly relevant. Here, structures span the spectrum from offshore platforms to warships and submarines to ocean liners, tankers, LNG and bulk carriers, as well as to yachts, catamarans and small pleasure craft. These are variously built from structural steels, aluminium alloys and carbon fibre or glass fibre composites. Shells, especially stiffened shell structures, due to their high strength-to-weight ratio, are able to meet the requirements outlined above and have been widely used in these engineering fields. However, shell buckling, as depicted in Figure 1(a) and (b) constitutes an unexpected catastrophic failure of thin shell structures; this should be fully understood and avoided in engineering practice. The traditional approach to shell design is to predict the buckling load, but experiments have shown that further weight savings are possible by allowing post-buckling to occur during operation [1]. For design and strength assessment of various types of stiffened shell structures, it has been shown that ultimate limit states (or ultimate strength) are a much better basis for this than the allowable working stresses [2]. The local and global buckling behaviours are important criteria for sizing and certification [3]. However, it is well-known that buckling is strongly affected by the mechanical properties of the material and the geometry of the structure, as well as contact conditions; these constitute complex synergistic effects of the controlling parameters. It has been commonly observed in instability phenomena that small variations in these parameters can result in widely different buckling behaviours [4]. Due to these factors, it is difficult to perform analysis of buckling initiation and growth. However, to improve the effectiveness of current stiffened shell structures used in different fields of engineering, a major research effort is currently underway.

Various emphases of buckling research can be found in the open literature. Das et al. [5] concentrates on buckling and ultimate strength assessment of ring stiffened shells as well as ring and stringer stiffened shells, involving various modes of buckling and various loadings, such as axial compression, radial pressure and combined loading, using the best state-of-the-art knowledge. Gaspar et al. [6] applied structural reliability methods to assess the implicit safety levels of the buckling strength requirements for longitudinal stiffened panels implemented in the IACS Common Structural Rules (CSR) for double hull oil tankers. Caputo et al. [7] carried out a numerical-experimental investigation into the post-buckling behaviour of two demonstrators representative of the bottom skin panel of an unpressurised aircraft fuselage. A brief examination of some of the research on the post-buckling elastic and plastic behaviour of plates and plate structures has been outlined [8]. The structural analysis and design technology for buckling-critical shell structures were discussed, and the future directions and challenges in shell stability analysis were presented [9]. Many countries attach great importance to research in this area by both the academic and industrial communities; research in these fields has been promoted by the funding of specific projects [10-14] to improve certification and design tools, as well as established design guidelines [15-17]. These research projects have made a significant contribution to the practical design of stiffened shell structures.

The key objective of this paper is to present a broad perspective of the recent research (2000-2012) done on the buckling behaviours of stiffened shells and panel structures. The literature is collated and categorised based on two main research methods, namely: numerical analysis and experiment, used to study various buckling problems of various stiffened structures under various loading conditions. Another method, optimisation, is also important but is considered to be beyond the scope of the present paper. The first aspect of this review will focus on the application of the finite element method (FEM) and finite strip method (FSM), as well as other analysis methods. The second aspect of this review will concentrate on experiments which apply the respective different loading conditions. In fact, as with any complex engineering problem, it is necessary to apply a combination of research methods in order to obtain satisfactory results. Generally, experiment and analysis may be conducted at the same stage: therefore, many articles may be cited more than once in this paper.



(a)

(b)

Figure 1: Shell buckling examples: (a) buckled water tower; and (b) buckled wine tanks [http://shellbuckling.com/buckledShells.php].

2. ANALYSIS METHODS

2.1 FINITE ELEMENT METHOD (FEM)

Among the known solution techniques, FEM is certainly the most favoured method to deal with various buckling and post-buckling behaviours of different stiffened shell structures. Numerical simulation and extensive parametric analyses can provide a reference for structural design and optimisation. Especially, FEM can be used to gain an understanding of important local effects which are difficult to measure in experiments [18].

2.1 (a) Numerical Simulation Using FEM-based Commercial Codes

The buckling behaviours of stiffened panels can be investigated using commercial finite element software packages (ABAQUS, ADINA, ANSYS, DYNA, NASTRAN, etc.) because they have strong modelling and solving functions. Many buckling engineering problems, such as local buckling of a rectangular plate area with longitudinal stiffeners in one direction and heavy transverse girders in the other direction, as shown in Figure 2 [19], global buckling behaviour of a composite stiffened panel with three connection methods (see Figure 3) [20] as well as post-buckling behaviour of conventional aircraft fuselage panels (flat riveted panels, see Figure 4) [21, 22] can be directly solved by skillfully using these software packages. In addition, geometrically nonlinear finite element modelling of buckling analysis for stiffened cylindrical shells under axial compression and external local load was carried out by Krasovsky et al. [23]. This numerical approach can be applied to the design of real axially compressed circular cylindrical shells under external local quasi-static loads. Two-dimensional finite element models applied to large fuselage-representative structures were analysed to investigate the failure in skin-stiffener interfaces under post-buckling loads [24]. Moreover, various parameters and many factors, like initial imperfection, geometric configurations, and so on, which have an effect on the buckling behaviour, are taken into account during analysis and simulation.

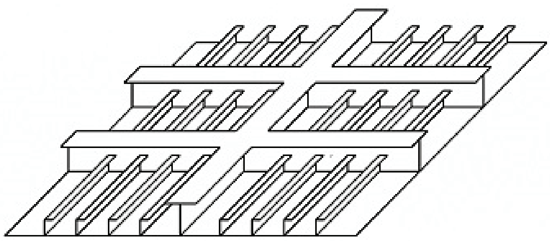


Figure 2: Stiffened panel [19]. Reproduced under license from Elsevier.

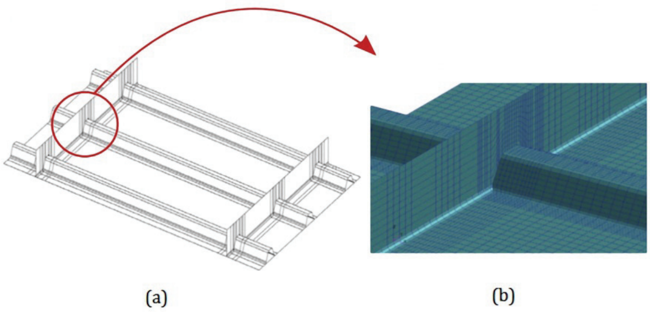


Figure 3: (a) Modelling of the composite stiffened panel (isometric view); and (b) detailed view of the mesh [20]. Reproduced under license from Elsevier.

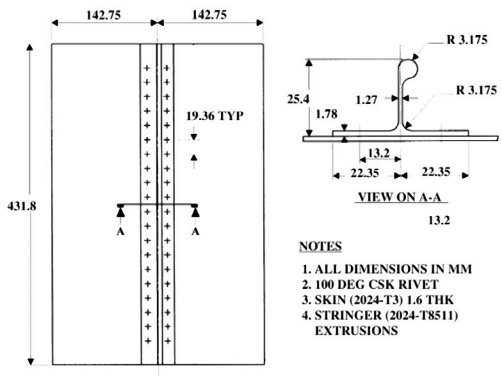


Figure 4: Flat riveted panel (a flat skin stiffened by a single stringer) [21]. Reproduced under license from Elsevier.

Effect of initial imperfection

It is well known that initial imperfections (including initial deflections and welding residual stresses) are some of the most important factors that impact on buckling. To avoid any discrepancy between experiment and analysis, almost all researchers have considered initial imperfection in studies on buckling or post-buckling behaviour of stiffened shell and plate structures.

The effect of imperfection shape and amplitude on critical loads of carbon fibre reinforced plastic (CFRP) cylindrical shells was investigated. It was concluded that the initial geometric imperfections have a great influence on the dynamic buckling of the shells, but the sensitivity to initial geometric imperfection depends on the lay-up of the laminated shells [25, 26]. Zhao and his co-worker did the same research for a complex steel silo transition junction structure and found that the imperfections lead to a significant reduction in the final collapse load of the junction, while the amplitude of the imperfection has little effect on the collapse load [27, 28]. Degenhardt et al. [13] performed a nonlinear structural analysis on a test panel to investigate skin–stiffener debonding in fuselage-representative structures, by considering geometrical imperfections. The results show that the global geometric imperfections at the panel edge are likely to directly influence the panel buckling shapes, while the skin imperfections had an almost negligible effect on the results, with only the transition from local to global buckling showing a slight difference. For dynamic buckling, Yaffee and Abramovich [29] applied the ADINA finite element code to calculate dynamic buckling loads of an aluminium externally stringer stiffened cylindrical shell (see Figure 5). The initial geometric imperfections, as well as the load with a half-wave sine shape, have a great influence on the dynamic buckling.

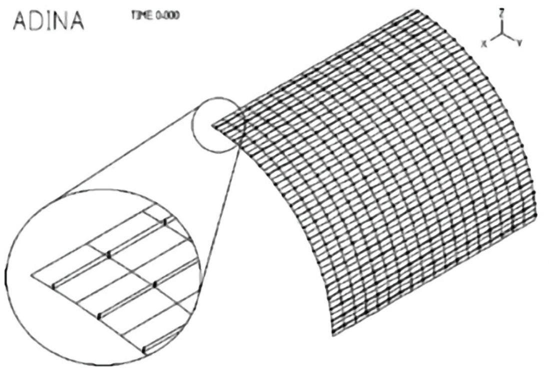


Figure 5: Finite element model of stiffened cylindrical shell [29]. Reproduced under license from Elsevier.

The effects of the heat-affected zone (HAZ) on the buckling and post-buckling performance of aluminium structures, the post-buckling behaviour and ultimate strength characteristics of stiffened aluminium plates under axial compression [30, 31] and under combined axial or in-plane compression and lateral pressure [32, 33] were investigated. According to this work the analytical results are affected by the HAZ, and the reduction of ultimate strength is up to 34%. The load eccentricity also affects the ultimate strength significantly. However, the ultimate capacity is not sensitive to welding residual stresses in aluminium stiffened panels subjected to axial compression, while in plates subjected to combined load, the welding residual stresses lead to a reduction in the ultimate capacity; the amount of this reduction is a function of both the type of stiffener and also the value of lateral pressure.

However, initial imperfections do not have a significant effect on the buckling behaviour or cracking of some structures. The critical buckling loads of optimised flat and curved composite plates with a geometric imperfection under shear and in-plane bending were calculated [34, 35]. Imperfection sensitivities are not significant for plates, while imperfection sensitivity is greater for panels with smaller aspect ratios, and those with greater curvature (see Figure 6). For the structure shown in Figure 7(a) and (b), the post-buckling behaviour of stiffened composite panels tied together with the loading frame subjected to in-plane shear loads was analysed, with the numerical results showing that the post-buckling behaviour of the panels prior to collapse was not significantly affected by the geometric imperfections and their magnitudes [36].

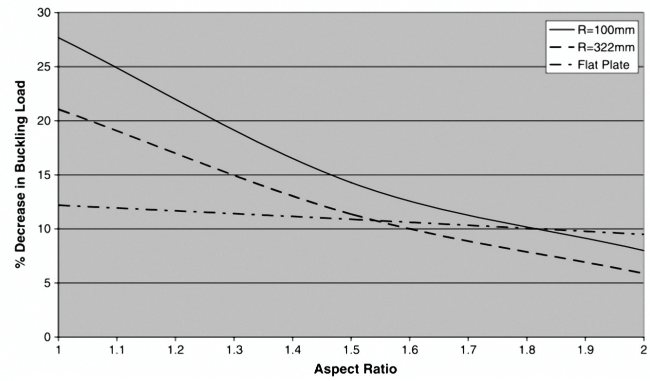
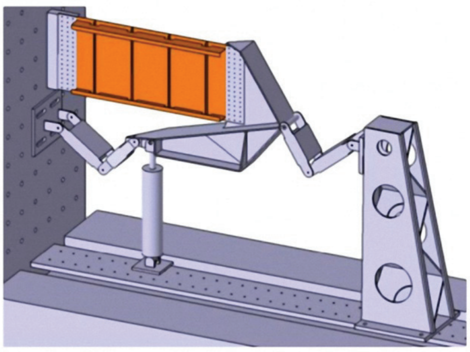
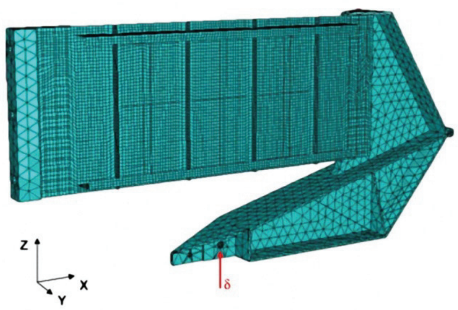


Figure 6: Imperfection sensitivity of plates and panels with differing radii of curvature and aspect ratios [35]. Reproduced under license from Elsevier.



(a)



(b)

Figure 7: (a) Test device and (b) finite element model of stiffened composite panels with the loading frame [36]. Reproduced under license from Elsevier.

Effect of geometry configuration factors

The geometry configuration factors, including number and cross-shape or profile of stiffener, and lay-out or configuration of stiffeners, rib numbers as well as the stacking sequences of CFRP, have a great influence on the buckling behaviours of stiffened shell structures. Changes of buckling modes were captured by varying stiffener slenderness, number of stiffeners and tapering angle, treated as design parameters [37]. The role of stiffeners to increase the buckling capacity of plates without increasing the plate thickness was researched, and it was concluded that by stiffening a flat rectangular plate, its critical shear stress increases. The amount of this increase depends on the aspect ratio and both the type and number of stiffeners [38]. FEM studies on the influence of stiffener cross-section with rectangular (R), L and T shapes, as well as the spacing of the stiffeners and the presence of rigid transverse stiffeners, on the buckling behaviour of stiffened isotropic plates were conducted [39-41]. The extreme values of maximum collapse stress σ_{ult} are related to the plates with an L shape stiffener, because an L shape stiffener does not have a symmetrical geometrical shape. Further research regarding the effects of the number of helical ribs and grid types on buckling was done by Yazdani and Rahimi [42]. Obviously, the maximum buckling load is increased by adding rib or hoop rings to the structure, but under axial loading, increasing the number of helical ribs is more effective than adding hoop rings and changing the grid types. The effects of some parameters (fibre orientation, skin thickness and elastic material properties) on buckling analysis of a stringer-stiffened composite cylinder were studied [43].

Zingoni and Balden [44] carried out a numerical study on the buckling behaviour of lightly stiffened elliptic paraboloidal steel panels intended for use as long-span shuttering for lightweight concrete bridge decks, walkways and floors. The buckling strength of the panels is strongly dependent on the rise (h/b) of the panel. Furthermore, the shallow elliptic paraboloid is far more efficient than the shallow sinusoidal shell in resisting buckling, especially as the rise is increased and/or as the aspect ratio (b/a) is increased.

In addition, Fenner and Watson [45] investigated the effect of fillet radius along the line junction between the stiffener webs and skin on buckling performance of a stiffened panel by using the finite element (FE) program MSC NASTRAN. The initial buckling performance can be significantly improved by increasing the fillet radius. A 5mm radius leads to an increase of 34% in local buckling load performance for a skin portion having breadth-to-thickness ratio of 100; the associated overall buckling load increases by 1.8%.

Effect of in-service damage (corrosion, cracking)

Some studies concerning buckling or ultimate strength have been performed on stiffened steel plates with corrosion damage, either numerically or analytically. The effect of corrosion thinning on overall collapse was explored [46, 47]. The ultimate strength characteristics of plate elements with pit corrosion wastage under axial compressive loads and in-plane shear loads were studied, and closed-form formulae for predicting the ultimate strength of pitted plates using the strength reduction (knock-down) factor approach were derived [48, 49].

Nakai et al. [50] investigated the effect of pitting corrosion on the basic mechanical properties of plate members which consisted of web, shell, stiffeners and face plates under compression. This was an investigation into the post-buckling behaviour and ultimate strength of imperfect corroded steel plates used in ship and other marine-related structures. It was concluded from this work that finite element analyses are able to simulate plate deformation with pit corrosion.

Satish Kumar and Paik [51] estimated the buckling loads of plates with cracking damage, such as an edge crack or central crack, under uniaxial compressive load, biaxial compressive load and in-plane shear, by using a finite element method based on hierarchical trigonometric functions. In the following year, the same authors used ANSYS nonlinear finite element analyses to investigate the ultimate strength reduction characteristics of plate elements, due to cracking damage with varying size and location [52]. In addition, progressive failure of stiffened composite panels, including ply damage modes such as matrix cracking, fibre-matrix shear, and fibre failure, were considered and represent the damage scenario in the post-buckling regime [53]. Sidharth [54] stated the importance of, and reviewed the current developments in, the FE analysis technique used to study the corrosion effect on plates.

Effect of element type, density and FE solver

Because the element type, mesh density, convergence criterion and choice of FE solver may impact on the buckling or post-buckling performance, some researchers have been concerned about these issues when they use software to solve buckling and/or post-buckling problems.

An extensive sensitivity analysis, including mesh density, element types, the codes and the numerical procedures (number of steps, etc.), was carried out by the Committee III.1 "*Ultimate Strength*" of ISSC'2003 in the framework of a benchmark on the ultimate strength of aluminium stiffened panels [31]. However, the difference between the minimum and maximum values is very small, and is probably induced by those factors in parentheses. The effect of mesh density on buckling or post-buckling behaviour has also been investigated [25, 41, 55-58].

The effect of different model generators and FE solvers on the predicted collapse pressure of submarine hulls with T-section ring-stiffeners was studied by MacKay et al. [59]. Further, the influence of modelling and solution methods on the FE simulation of the post-buckling behaviour of stiffened aircraft fuselage panels was studied by Linde et al. [22]. As long as the general methodology was the same, the accuracy of the collapse predictions was not very sensitive to using different combinations of those programs. In addition the element, mesh, idealisation and material modelling selection for the computational post-buckling analysis of fuselage stiffened panels loaded in shear was investigated by Murphy et al. [60].

2.1 (b) Application and Development of Finite Element Method

The literature above is all on the application of commercial software to deal with the buckling and post-buckling problems of stiffened shell structures. However, often for some specialised areas, or in order to investigate the influence of geometric parameters on the buckling behaviour of stiffened shell structures, or to determine structural parameters at the design stage, shorten computing time, or improve accuracy and convergence, it is necessary to conduct a parametric study or produce add-on routines to the existing commercial software by developing in-house codes for new analysis approaches. More often than not, in order to research the buckling behaviour of special structures more expediently, new elements are developed for modelling or for special analysis purposes.

Finite element parametric analysis on buckling

Parametric studies of stiffened steel plates subjected to axial compression [61, 62] as well as combined uniaxial compression and bending moment [63] were conducted to identify the various parameters that govern the buckling behaviour (four forms, see Figure 8). A parametric study is discussed to check the effects of geometrical parameters on the specific buckling load for different kinds of cylindrical grid stiffened composite shells [64]. Parametric simulations were performed to study the local shear buckling of thin-walled cassette structures [65] and to study the effect of important design parameters on the initial buckling load of stiffened composite panels [66]. Parametric and comparative studies were conducted for different plate aspect ratios, plate thickness-to-length ratios, degrees of layer orthotropy, ply orientations, and stiffener depth-to-plate thickness ratios, to discover the interaction between the lateral buckling of the stiffener and the buckling of the laminate [67]. The effect of various parameters like shell geometry, stiffening scheme, static and dynamic load factors, stiffener size and position, and boundary conditions are considered in buckling and dynamic instability analysis of stiffened panels subjected to uniform in-plane harmonic loads along the boundaries [68, 69].

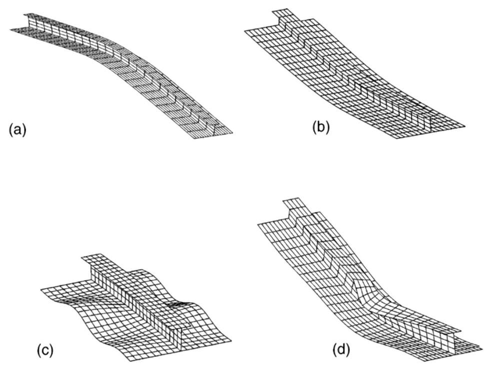


Figure 8: Typical buckling modes: (a) overall buckling (plate induced); (b) overall buckling (stiffener induced); (c) plate buckling; and (d) stiffener tripping [61]. Reproduced under license from Elsevier.

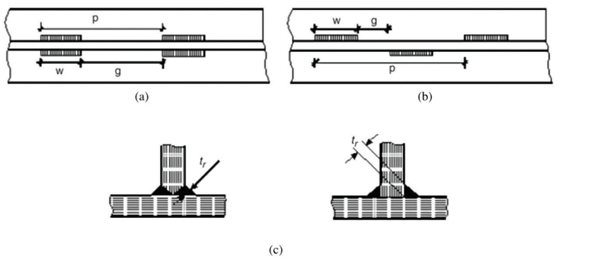


Figure 9: Typical intermittent fillet welds: (a) chain intermittent fillet welding; (b) staggered intermittent fillet welding; and (c) the throat thickness of fillet welds [70]. Reproduced under license from Elsevier.

Khedmati et al. [70] carried out a parametric study to find the permissible gap length of intermittent fillet welds (see Figure 9) to prevent the local buckling of members and premature failure of the whole stiffened plate. Morozov et al. [71] also carried out a parametric analysis to investigate the effects of the length of the shells and the angles of orientation of the helical ribs on buckling of composite cylindrical lattice shells subjected to tension/compression, bending in two planes, and torsion.

Some parametric studies on simply supported laminated composite blade-stiffened panels subjected to in-plane shear loading were carried out by changing the panel orthotropy ratio, stiffener depth, number of stiffeners, smeared extensional stiffness ratio of stiffener, and so on [72]. To assess the influence of initial geometric imperfections and boundary conditions on the dynamic buckling capacity, Less and Abramovich [73] performed a wide range of parametric numerical dynamic buckling analyses of a laminated composite stringer-stiffened curved panel subjected to an axial impact load by using ANSYS.

Development of new elements for buckling

Sridharan and Zeggane [74] studied the interaction of local and overall buckling in stiffened plates and cylindrical shells by using a specially formulated shell element, which has additional degrees of freedom to trigger and modulate the relevant local buckling modes together with the associated second order fields. In order to predict realistic behaviour in the post-buckling region, taking account of skin–stiffener debonding, Kim and Kim [75] introduced cohesive elements to build an accurate and realistic post-buckling model for a stiffened composite panel. The resulting global behaviours and failure loads were similar to the experimental results.

A layer-wise finite element formulation was developed for the buckling analysis of stiffened laminated plates. Degenerated shell elements and general 3D beam elements were used to model the stiffened thin or thick laminated plate; moreover, the interaction between the lateral buckling of the stiffener and buckling of the laminate was discovered [67].

To investigate the buckling and vibration characteristics of a tube-stiffened dome constructed in solid urethane plastic (SUP) [76] and the buckling performance of a corrugated circular cylindrical pressure vessel [77], the truncated varying meridional curvature axisymmetric element (see Figure 10), which has two nodal circles at each end with each node having four degrees of freedom, was developed to model them. To investigate the buckling behaviour of a ring-stiffened plate dome under hydrostatic pressure, a theoretical analysis via a finite element program called CONEBUCK was conducted by the same authors [78] using the same element described in the previous two references. In another investigation, the same authors [79] did further research on the plastic buckling of ring-stiffened conical shells under external hydrostatic pressure by using finite elements and incorporating the in-house axisymmetric shell program called RCONEBUR, which employs truncated conical axisymmetric elements (see Figure 11) with two nodal circles at each end, using small deflection elasticity theory. Using less than 20 of these elements, the buckling performance of this structure could be researched; the calculation efficiency was significantly higher than that of commercial software.

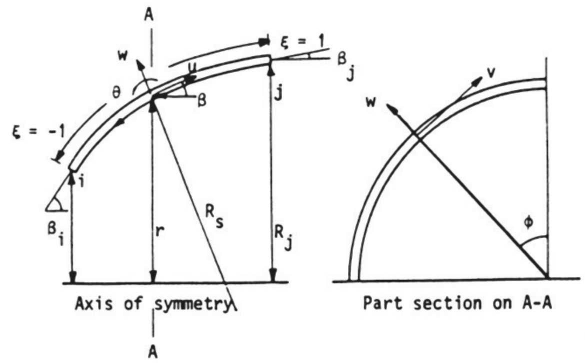


Figure 10: Varying meridional curvature annular element [76]. Reproduced under license from Elsevier.

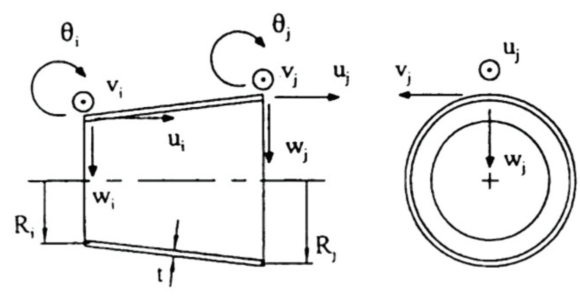


Figure 11: Truncated conical shell element [79]. Reproduced under license from Elsevier.

Nayak et al. [80] developed a new nine-node plate bending element with assumed strains based on a refined higher order theory, which includes the effect of initial stresses in the dynamic analysis of plates, to study the small deflection transient response of composite sandwich plates under the influence of initial stresses.

The developed element is free from any major defects like patch test failure, shear locking phenomenon and spurious zero energy modes due to use of the assumed strain concept. Ganapathi [81] developed a three-node shear flexible axisymmetric curved shell element based on the field-consistency principle, to study the dynamic stability behaviour of a clamped Functionally Graded Material spherical shell subjected to external pressure load. From a detailed study, it was observed that the lowest dynamic critical buckling pressure of a spherical cap significantly depends on the value of material power-law index, apart from geometric shell parameters.

Taking into account the non-uniform torsional response of the stiffener, Vörös et al [82] applied a new stiffener element with seven degrees of freedom per node and a coupling technique to determine the mode shape and buckling loads of plates or shells stiffened by beams of arbitrary cross-section. Patel et al. [68, 69] used the eight-noded isoparametric degenerated shell element and a compatible three-noded curved beam element to model and to investigate the static and dynamic instability characteristics of stiffened shell panels; the method of Hill infinite determinant was applied to analyse the dynamic instability regions. Rikards et al. [83] employed an isoparametric triangular finite element model to study the buckling and vibration of laminated composite stiffened shells and plates based on first order shear deformation theory. Prusty and Satsangi [84] presented a finite element buckling analysis of laminated stiffened plates and stiffened cylindrical shells using an arbitrarily-oriented stiffened shell formulation, which employed an eight-noded isoparametric quadratic element for the shell and a three-noded curved stiffener element for the stiffeners (see Figure 12), based on the concept of equal displacements at the shell–stiffener junction. In this formulation, the stiffener can be placed anywhere within the shell element, which obviates the constraints of aligning the mesh lines along the stiffeners. The same formulation was used to investigate the dynamic and buckling analysis, which resulted in accurate prediction of stiffener stresses with more computational efficiency [85, 86]. Subsequently, the free vibration and buckling performance of open and closed section stiffeners were investigated by carrying out finite element static, dynamic and buckling analysis [87]. A finite element model was developed to predict the periodically stiffened shell dynamic behaviour and to perform a buckling analysis by using Bolotin's method and Floquet theory [88].

2.2 FINITE STRIP METHOD (FSM)

The problem of unforeseeable computational time is inevitable if the finite element method is used to model and to provide accurate predictions of the buckling response of large scale structures [89]. However, the finite strip method is a technique which is less powerful and versatile than the finite element method, but is more efficient in terms of computation power in some situations. In fact, the finite strip method is a special finite element method, which replaces the continuous displacement shape function in the FEM with a piece-wise polynomial function. Therefore, much research on buckling or post-buckling behaviour of different structures has been done using applied FSM. Moreover, the method was developed and promoted to be more applicable to analysing the different buckling behaviours of various materials and various structures.

Using the finite strip method to establish the equation of equilibrium for rib-stiffened plates (see Figure 13), Xie and Ibrahim [90] studied buckling mode localisation in rib-stiffened plates with randomly misplaced stiffeners. The finite strip method is suitable for studying the localisation phenomenon in buckling models of rib-stiffened plates.

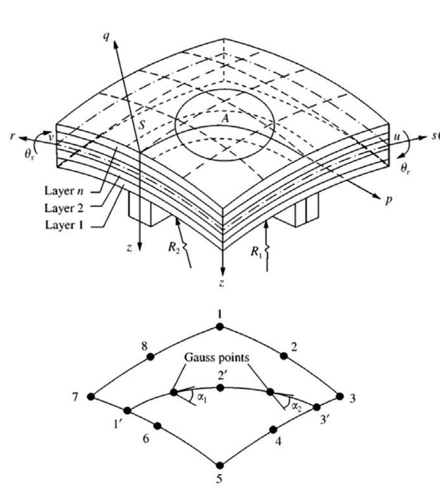
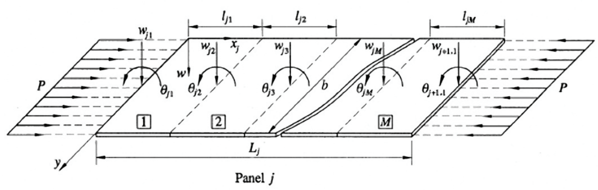


Figure 12: Stiffened shell with an arbitrarily-oriented stiffener [85]. Reproduced under license from Elsevier.



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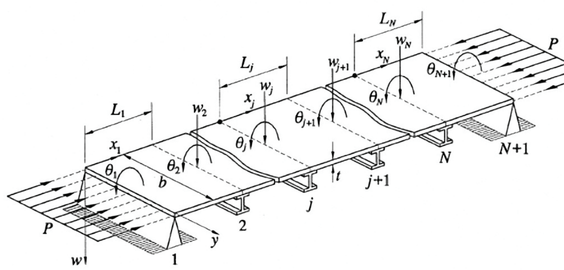

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Figure 13: Rib-stiffened plate: (a) finite strip discretisation of rib-stiffened plate; and (b) rib-stiffened plate under axial compressive load [90]. Reproduced under license from Elsevier.

The finite strip method was successfully applied to calculate the buckling load of stiffened panels in wing box structures [91]. At the same time, the author further developed the finite strip method and extended its application scope to determination of the post-buckling stiffness of these panels. Subsequently, Dawe and Yuan [92] developed a B-spline finite strip method (FSM) for predicting the elastic buckling of rectangular sandwich plates under the action of direct stress and shear stress applied to the faceplates. The in-plane displacements vary quadratically through the thickness, while the out-of-plane displacement varies linearly. Multi-level sub-structuring within the super-strip concept was encompassed in this efficient procedure, which can determine critical buckling stresses and mode shapes. The method can predict both overall buckling and local faceplate wrinkling in a powerful, general and efficient unified formulation. For analysis of stiffened structures, where the buckling mode is characterised by simultaneous in-plane and out-of-plane displacements, Dawe [93] proposed a polynomial finite strip method (PFSM) model based on the use of both classical plate theory and first-order shear deformation plate theory, which can also be used to analyse the behaviour of flat and curved structures.

Because the classical finite strip method emerged as a modified FEM with a reduced dimensionality, it was readily applicable to composite materials, while also being improved to deal with some complex cases of geometrical, boundary, and loading conditions. Razzaq and El-Zafrany [94] applied a new concept to the finite strip method for the derivation of an efficient element for buckling and nonlinear stress analysis of folded and stiffened plates, made of composite layered materials. Mindlin’s plate-bending theory was employed for the derivation of the efficient element.

Möcker and Reimerdes [95] used the finite strip method to separate the structure, and simulated the buckling and post-buckling behaviour of curved stiffened composite panels quickly and accurately. In contrast to the conventional finite strip method, the application of the approach proposed in this paper enables the determination of element stiffness matrices that represent an analytical solution of the governing differential equations.

Eccher et al. [96] used the isoparametric spline finite strip method (ISFSM) to perform an elastic buckling analysis of perforated flat and stiffened plates. Recently, Yao and Rasmussen [97] extended the application of ISFSM to a study on material inelastic and geometric nonlinear analysis. A number of numerical examples, including analyses of flat plates with different material plasticity models, a classical nonlinear shell problem, perforated flat and stiffened plates, and perforated stiffened channel section storage rack uprights, were used to demonstrate the reliability and efficiency of ISFSM.

With the increasing use of composite laminates in many demanding applications, the layer-wise B-spline finite strip method was developed with consideration of delamination kinematics to study the buckling, post-buckling and delamination propagation in debonded composite laminates under compression [98, 99].

To study the large deflection and elastic post-buckling behaviour of stiffened plates, conventional FSM cannot be used because this technique ignores the important influence of the buckling modes interaction. To overcome this drawback of conventional FSM, Milašinović [100] developed the harmonic coupled finite strip method (HCFSM) for the geometric nonlinear analysis of thin plate structures with stiffeners under multiple loading conditions. The HCFSM is more universal when dealing with a large deflection and the post-buckling problem, because it is an extension of a finite strip method used to deal with the nonlinear response to multiple loading conditions.

More recently, a new semi-energy FSM was developed based on the concept of first-order shear deformation plate theory (FSDT) in order to attempt the large deflection solution and the post-buckling solution for thin and relatively thick anti-symmetric angle-ply composite laminates subjected to uniform end-shortening [101, 102]. Study of the results has provided confidence in the validity and capability of the developed FSM in handling the post-buckling problem of anti-symmetric angle-ply laminates.

Based on the Kirchhoff–Love theory and making use of the Kantorovich method, Ruocco and Fraldi [103] performed an accurate sensitivity analysis for the buckling loads and modes of prismatic flat and curved isotropic stiffened shell assemblies, by adopting different nonlinear kinematical models, and derived the general buckling equation by using the semi-analytical approach. However, because the numerical procedure is based on a closed-form solution of the equilibrium equation, the approach can be seen as belonging to the semi-analytical finite strip method family. The semi-analytical finite strip method can be also based on the Mindlin–Reissner plate theory: Bui and Rondal [104] studied the buckling behaviour of highly stiffened thin-walled sections, for which the Mindlin–Reissner finite strips are more accurate than the Kirchhoff ones.

2.3 OTHER ANALYSIS METHODS

Buckling and/or post-buckling behaviour of stiffened shell structures may be approached with various numerical analysis methods, e.g. the finite element method and finite strip method, semi-analytical, as well as analytical methods. Most of the analysis methods are relatively simple, but robust and highly accurate.

The differential quadrature (DQ) method was applied to analyse the buckling problem of various stiffened structures, such as rectangular plates [105], spherical shallow shells [106], and doubly curved shallow shells [107], because it is simple, computationally efficient and highly accurate. Following this, the differential quadrature element method (DQEM) was used for the first time to obtain buckling loads of stiffened circular cylindrical panels subjected to uniformly distributed axial compression [108].

The semi-analytical approach was applied to study the buckling and post-buckling field of stiffened plates [109-114]. In order to estimate the stochastic distributions and the correlations between the first buckling load (or local buckling load), the global buckling load and the collapse load of stiffened panels, a semi-analytic probabilistic analysis was performed [115]. A fast semi-analytical model has been presented, which can be used to assess the local post-buckling behaviour of stiffened panels [116, 117].

Kidane et al. [118] and Wodesenbet et al. [119] developed a smeared model to solve the buckling problem of a grid-stiffened composite cylinder, by considering the moment effect and the exact geometric configuration of the stiffeners. Furthermore, classical shell theory and the smeared stiffeners technique were used to study the nonlinear static post-buckling of eccentrically stiffened functionally graded plates and shallow shells under uniform external pressure, including temperature effects [120] as well as conical panels under mechanical loads [121].

The post-buckling analysis of stiffened braided thin shells subjected to combined loading from external pressure and axial compression by a perturbation method is reported by Zeng and Wu [122]. The results showed that the buckling loads are significantly influenced by braid angle and stiffeners; the imperfection parameter has a significant effect on the buckling load and post-buckling strength. The dimensionless form of axial compression load is decreased by increasing the imperfection parameter.

Schneider and Ribakov [123] used a quasi-static analysis method to complete a thin-walled circular cylindrical steel shell collapse analysis under constant shear loading. The method can be used to distinguish local and global instability points, and to determine the experimentally observed post-buckling strength.

To avoid excessively time consuming nonlinear FE analyses of a whole aircraft fuselage, Heitmann and Horst [3] adopted a very fast quasi-nonlinear FE analysis with a coarse mesh using semi-empirical methods, for the assessment of the effective compression or shear stiffness of a rectangular stiffened metallic panel under combined compression and shear force in the post-buckling range. The method has advantages for the general combined compression and shear load case. To develop a fast and efficient local buckling and post-buckling solution for stiffened panels, the Galerkin method was used to study the elastic and inelastic local buckling of stiffened plates [124, 125], and the first-order shear deformation theory (FSDT) mesh-free Galerkin method was used to study the elastic buckling behaviour of stiffened structures [126-129].

Stamatelos et al. [130] presented a methodology based on a two-dimensional Ritz displacement function (*pb-2 Ritz*) for the analytical assessment of local buckling and post-buckling behaviour of isotropic and orthotropic stiffened plates, as well as for the prediction of the post-buckling response of stiffened panels whose skin had undergone local buckling.

Byklum and Amdahl [19] derived a computational model for analysis of local buckling and post-buckling of stiffened panels, which is more accurate than existing design codes, and more efficient than nonlinear finite element analysis; it also suits any combination of biaxial in-plane compression or tension, shear, and lateral pressure.

Najafizadeh et al. [131] studied the static buckling behaviour of functionally-graded cylindrical shells stiffened by rings and stringers, under axial compression loading by using equilibrium and stability equations, which were derived by using the Donnell nonlinear strain-displacement relations and Sander's assumption. The results show that the inhomogeneity parameter and geometry of the shell significantly affect the critical buckling loads.

To assess the reliability of the post-buckling compressive strength of laminated composite plates and stiffened panels under axial compression, Chen and Guedes Soares [132] developed a new approach based on progressive failure analysis, the finite difference method and an improved first-order reliability algorithm.

Closed-form analytical formulae for the buckling loads of compressively loaded orthotropic composite and isotropic plates braced by longitudinal stiffeners were derived [133-135], which can be conveniently used in practical applications. The closed-form analytical solution exhibits a very satisfying agreement with the exact transcendental solution, and with numerical results generated by the Ritz-method. Bisagni and Vescovini [136] derived closed-form solutions for the linearised local and global buckling loads, and implemented a semi-analytical procedure to study the nonlinear local post-buckling field.

2.4 SUMMARY OF ANALYSIS METHODS

The finite element (FE) method is increasingly being used to analyse the buckling behaviour of stiffened shell structures made from various materials. For relatively simple buckling problems, commercial FE software is frequently and directly employed to complete numerical simulations. New elements developed for special structures can avoid excessive computing time and the deficiencies of the existing software. The finite strip method (FSM), as a special finite element method, replaces the continuous displacement shape function in the FEM with a piece-wise polynomial function. For some complex structures, such as prismatic ones, constituted by flat or curved plate components rigidly connected along their longitudinal edges to form arbitrary cross-section profiles, FSM can substitute for the FEM due to its accuracy, lower computational times and ease of data preparation [137]. It may efficiently reduce the order of the stiffness matrix and improve the calculation efficiency for some particular cases.

Other analysis methods, including numerical methods, semi-analytical methods and analytical methods, used to solve buckling problems involving stiffened shell structures, are also the subject of research in the most recent literature. They are relatively simple, but robust and highly accurate.

3. EXPERIMENTS

Simulation and theoretical solution are inherently approximate in nature because of the assumptions and hypotheses needed. In order to validate calculations and models, the use of experimental data is the best method. Moreover, many complex engineering problems cannot easily be simulated or solved using existing theories. For example, to investigate the ultimate strength of a stiffened panel, in the absence of failure criteria, the peeling between skin and stringers encountered in the tested panels cannot be allowed for in the development of a finite element model. In addition, the application of post-buckling design to composite primary structures such as the fuselage and wings of an airplane, with components capable of operating safely well beyond the buckling load, strictly depends on the development of predictive models of post-buckled stiffened structures and the verification of such models using well-documented experimental results. However, almost all experiments on buckling or post-buckling of stiffened panel structures have been mainly model tests and concentrated in the laboratory, because large subcomponents are expensive to fabricate and test, while structural scaling approaches can provide results to be used to develop and design full-scale structures.

Prediction of the buckling performance of stiffened shell structures is of prime interest in structural experiments. However, experiments on the buckling or post-buckling behaviour of stiffened shells or panels may have different characteristics, because stiffened shells or panels with different geometries and made from different materials are subjected to various loads and used in various engineering industries.

3.1 UNIAXIAL COMPRESSION

3.1 (a) Isotropic Materials

Aalberg et al. [138] carried out axial compression tests on longitudinally-stiffened aluminium panels of alloy AA6082 temper T6, connected by longitudinal welds with open section (L shape) and closed section, respectively. Rønning et al. [139] performed another experiment on specimens of the same material with the same stiffeners, only with the loading acting perpendicular to the stiffeners, and in the plane of the plate. For the former tests, two deformation modes were observed in the experiment: these being flexural buckling and collapse initiated by stiffeners tripping. With regard to the latter tests, two different deformation modes were observed: global flexural buckling and local buckling of the plate elements between the stiffeners. Compared with the European standard for aluminium structures, the experimental capacity exceeded the design value.

Experiments using concrete-filled steel tubular (CFT) stub columns with welded longitudinal stiffeners under axial compression were carried out to investigate the effectiveness of longitudinal stiffeners in delaying local buckling of the steel tubes [140, 141]. The primary parameters considered in the test program were the height-to-thickness ratio of the steel tube, the stiffener rigidity, load eccentricity and slenderness ratio. According to the tests, the longitudinal stiffeners can delay the local buckling and improve the lateral confinement on the concrete core. The increment of moment of inertia of the stiffeners cannot improve the ductility of stiffened CFT columns significantly. As for the stiffened steel tubular stub columns with normal concrete (NC) or with steel fibre reinforced concrete, the buckling mode and buckling shape are the same.

To systematically study the influence of the following structural factors, including number of stiffeners, stiffener eccentricity sign, shell length and edge fixing requirements, on the mechanism of stringer shell carrying capacity exhaustion, Krasovsky and Kostyrko [142] performed some experiments on small-sized specimen steel shells, which were stiffened with identical equidistant longitudinal thin-walled stiffeners of angular profile, made of the cold-rolled stainless steel grade X18H9H under compressive force.

To investigate the influence of stiffener geometry on the ultimate strength of the stiffened panels under compression, eight tests of eight three-bay stiffened panels with associated plate made of very high tensile steel S690, were conducted by Gordo and Soares [143]; following this the same authors performed an extended experiment on long stiffened panels under axial compression until collapse, in order to study the effect of space framing on the strength of stiffened panels [144]. Four types of stiffened panels with three bays longitudinally were made of mild or high tensile steel for bar stiffeners, and mild steel 'L' and 'U' stiffeners, in the tests. Recently, Gordo and Soares [145] performed further similar experiments to analyse the influence of stiffener geometry on the ultimate strength of stiffened panels under compression.

To verify an equation for the minimum required stiffness of longitudinal stiffeners attached on compression plates, Choi et al. [146] conducted an experimental study of nine test specimens of stiffened steel plate, which were developed as a full model type including subpanels bounded by adjacent longitudinal stiffeners and adjacent transverse stiffeners or diaphragms, multiple numbers of stiffeners, and end boundary conditions. During this experiment, for longitudinally stiffened panels, there are three possible initial imperfection types: out-of-flatness of a subpanel, out-of-straightness of a stiffener, and stiffener camber deflection (see Figure 14). The out-of-plane stiffener camber deflections are relatively larger than the others, and they are likely to induce a symmetric buckling mode.

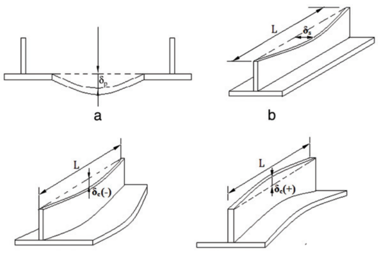

Figure 14: Typical initial imperfections of stiffened panels: (a) out-of-flatness of a subpanel; (b) out-of-straightness of a stiffener; (c) stiffness camber deflection [146]. Reproduced under license from Elsevier.

To investigate distortional buckling, and the interaction between local buckling and distortional buckling of longitudinally stiffened plates, Kwon and Park [147] carried out a series of compression tests on longitudinally stiffened plates made of mild steel SM400. The compression tests indicated that the critical buckling mode was dependent mainly on the rigidity of the longitudinal stiffeners and the width-to-thickness ratio of the sub-panels. Longitudinally stiffened plates undergoing interaction between local buckling and distortional buckling showed a significant post-buckling strength reserve, regardless of the dominant buckling mode, this being either distortional bucking or a mixture of local and distortional buckling.

3.1 (b) Anisotropic Materials

Falzon et al. [148] performed an experiment to investigate the post-buckling behaviour of a blade-stiffened composite panel under uniaxial compression. According to experimental observation, the failure was initiated by mid-plane delamination at the free edge of the post-buckled stiffener web at a node-line. The critical shear stress was calculated from strain gauge measurements, and was found to agree well with the shear strength obtained from a three-point bending test of the web laminate.

Scaling effects in complex composite structures have not been adequately investigated, and the traditional approaches to laminate thickness scaling have often proven unsatisfactory, due in part to their inability to model the inter-ply bond mechanism. Rouse and Assadi [149] carried out experiments to study the buckling response and failure of full-, half-, and quarter-scale stiffened-skin graphite-epoxy panels subjected to compressive uniaxial loads. The experimental load-shortening results are shown in Figure 15.

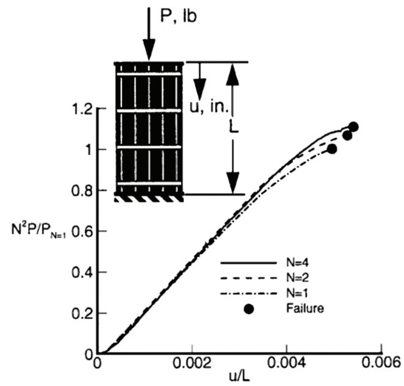

Figure 15: Summary of normalised specimen end-shortening results from experiments (*P* is the applied load; *N* is the geometric scale factor where *N*=1, 2, or 4 for the full-, half-, and quarter-scale specimens, respectively) [149].

The experimental data suggest that all of the specimens buckled at approximately the same buckling strain. Nine Hexcel IM7 (12K)/8552(33%) graphite-epoxy blade stiffened composite panels were tested at the Aircraft Structures Laboratory of the Technion, Israel Institute of Technology. The uniform axial compression load was gradually increased up to failure of the specimens at room temperature in order to study the buckling behaviour in detail [150].

Hosseini-Toudeshky et al. [66] performed experiments to understand the buckling behaviour of the typical light airplane wing nose and main rib constructions, made of composite materials either stiffened by P.V.C. foam or integrated vertical beads under compression. By comparing the experimental results, the conclusion was reached that using beaded web can improve the composite web resistance to instability more so than sandwiched web construction.

Lanzi [151] carried out experimental tests to investigate the possibility for composite stiffened structures to carry axial load in post-buckling fields, as well as the damage and failure mechanisms leading to collapse. In order to obtain a variety of different post-buckling behaviour types on panels with even and odd numbers of stringers (blade-type), with medium and small radii of curvature, and with different skin thicknesses, buckling and post-buckling experiments on axially compressed, stiffened CFRP curved panels were carried out by Zimmermann et al. [58]. A comprehensive experimental database for design validation was also established. In the case of excellent bonding, severe stress concentrations may cause delaminations and fracture in the skin or in the stiffener flanges at these locations. Simpler test methods consisted of a compression experiment with clamped edges to study the bending behaviour during post-buckling [89]. Post-buckling failure behaviour and strength were investigated in compression tests of hat stiffened composite panels, manufactured with different bonding methods and different stiffener section shapes [152].

Reinoso et al. [153] designed a hermetic box to carry out experimental tests to investigate the buckling and post-buckling behaviour of a stiffened cylindrical composite panel under uniform pressure load. A special geometric imperfection measurement procedure was proposed to measure geometric imperfections on the panel surface between the stringers, once the specimen (as a part of a real aircraft) is located in the experimental device. The tests were performed in the laboratory for a single panel. A total maximum load level of 3.5 times the critical buckling load was obtained from numerical analysis using ABAQUS/Standard.

3.2 EXTERNAL PRESSURE

Ross and Etheridge [76] studied the buckling and vibration characteristics of a prolate hemi-ellipsoidal tube-stiffened dome under external water pressure. According to the experimental results, the buckling pressure can be increased by 35.5% because of the tubes, but the internal pressure of a tube was ineffective in increasing the buckling pressure.

The buckling performance of a corrugated (resembling swedge stiffened but unlike ring stiffened) circular cylindrical pressure vessel produced from carbon fibre, under external pressure, was investigated through experiment [77]. The experimentally observed buckling pressure was a little lower than the theoretical prediction because of slight initial geometrical imperfection. However, the authors advised that further testing is needed to confirm the trends in this study, and to provide a measure of the likely scatter from a larger sample of experimental models (the reason is that in the absence of stiffening rings, buckling of the shell would occur at pressures only a fraction of that required to cause axisymmetric yield of the structure). In 2004, the buckling of three ring-stiffened prolate domes under external hydrostatic pressure was reported by Ross et al. [154]. The effect of ring stiffening the domes was to increase their buckling resistance by factors varying from 4.43 to 5.72. In the following year, the same author and others [79] carried out another experiment to study the plastic buckling and destruction of ring-stiffened cones under external hydrostatic pressure. Then, in 2007, Ross and Little [155] conducted some experimental tests on three ring-stiffened circular conical shells that suffered plastic general instability under uniform external hydrostatic pressure (see Figure 16). The results of these tests showed that the experimental buckling pressure was only half of the theoretical value. In other words, for larger values of initial out-of-circularity, the so-called safety factor will have to be made much larger.

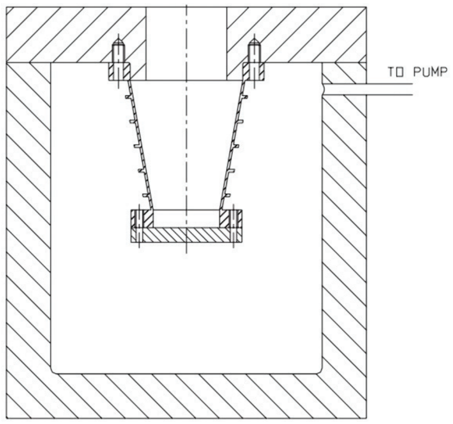

Figure 16: Vessel inside the test tank [155]. Reproduced under license from Elsevier.

In order to study the effect of corrosion damage on hull strength and stability, a cylindrical shell with T-section ring-stiffeners was machined from aluminium tubing and tested to collapse under external pressure by MacKay et al. [156]. This study showed that the collapse strength was reduced through high local stresses in the corroded region, leading to early onset of yielding and inelastic buckling.

3.3 COMBINED LOAD

Meyer-Piening et al. [157] performed tests on nine shells under axial load, as well as under combined axial compression and superimposed torsion, in order to determine the buckling loads of circular cylindrical shells with different laminate lay-ups. It was concluded that the buckling loads of cylinders which are imperfection-sensitive under axial loading may not be so sensitive to combined loads.

To study repeated buckling and its influence on the geometrical imperfections of stiffened cylindrical shells under combined loading (see Figure 17), Abramovich et al. [158] performed experiments using six stringer-stiffened 7075-T6 aluminium alloy shells on nominally simple supports. Each shell was subjected to various combinations of axial compression and external pressure. The experimental results showed that the repeated buckling of the shell did not induce any substantial damage to the shell (which was continuously monitored via measurement of the imperfections), except when buckling under axial compression.

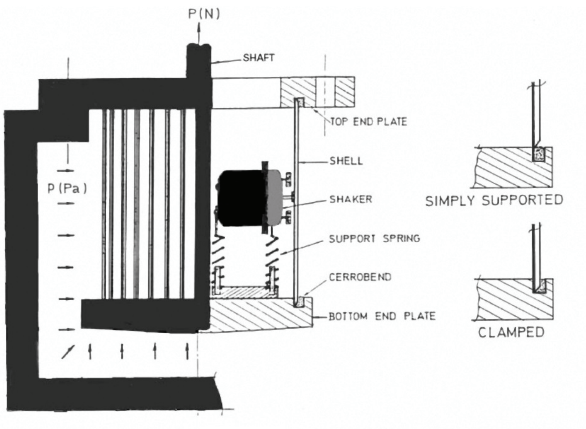

Figure 17: Detail of boundary conditions of shell and shaker attachment [158]. Reproduced under license from Elsevier.

To demonstrate the safe operation of post-buckled composite cylindrical stiffened panels as well as to provide part of a database for the development of a fast tool for reliable design of this type of structure, Abramovich et al. [159] carried out experiments on four torsion boxes under various combinations of axial and shear loads; the local buckling of their skins, their behaviour in post-buckling under combined loading, and their collapse under torsion were also studied. The tests indicated that the torsion-carrying capacity is dependent on stringer geometry and layup; also, the boxes have a very high post-buckling load-carrying capacity.

Few previous experimental studies have involved wind turbine towers, which exhibit specific geometrical and loading characteristics. In order to bridge this gap, Dimopoulos and Gantes [160] performed an experimental study on the buckling behaviour of cantilever shells with opening and stiffening (steel) that reflect the main geometric characteristics of wind turbine towers. The experimental work revealed that, even though the deformed post-collapse geometry was affected by the presence of initial imperfections, the collapse load for each type of shell (without opening, with opening, or with reinforced opening) was practically the same.

3.4 DYNAMIC LOAD

A grid-stiffened composite (see Figure 18) under transverse quasi-static loading and half-size panels under high velocity dynamic impact were tested. According to the experimental data, the panels absorbed more energy when loaded on the skin-side than on the rib-side. When loaded on the skin-side, skin buckling was observed; while when loaded on the rib-side, the skin remained intact [161].

Aiming at investigating the seismic performance of pure aluminium shear panels with stiffeners having different welded configurations, experimental tests under symmetric cyclic loading were carried out. It could be observed that the system dissipative capacity gradually increased due to stable post-critical behaviour. Finally, strength degradation occurred followed by collapse, with the development of global buckling. The test results are suitable to be applied to seismic protection of new and existing framed buildings [162].

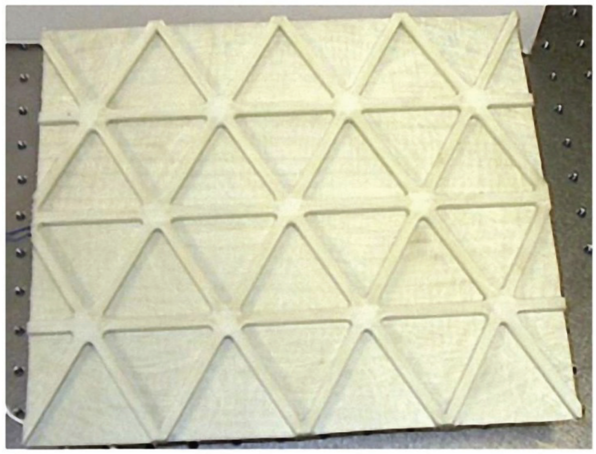

Figure 18: Full-size (300*250*7.5mm) laboratory scale E-Glass/PP isogrid composite plate [161]. Reproduced under license from Elsevier.

3.5 SUMMARY OF EXPERIMENTS

Experiments have been conducted to explore and better understand the buckling and post-buckling behaviour of stiffened composite structures. In this experimental testing, an electric signals system and optical system [such as strain gauges, Linear Variable Differential Transformer (LVDT) sensors and the Moire fringe technique] are used for the experimental data recording and display. To date, experiments to investigate the buckling/post-buckling performance of many different stiffened shell structures made from different materials subject to different loading conditions have been successfully performed. Although almost all experiments were carried out in the laboratory due to the high cost of fabrication and testing, the experimental results can be used to benchmark design criteria, to verify theoretical equations, or to predict the effect of initial imperfections on buckling.

4. CONCLUSIONS

This review article has presented the current knowledge on buckling and post-buckling behaviour of stiffened plate and shell structures, a subject that has been attracting many researchers, in terms of theoretical analysis, numerical simulation, and experiments. Based on the published research papers over the last decade, the ultimate goal of all this research work is to design stronger, safer and cheaper structures for various engineering applications, by understanding the stability status and the ultimate strength of stiffened shell structures.

All researchers in the field have reached a consensus that in the study of buckling and/or post-buckling behaviour of stiffened shell structures, a combination of experimental, numerical and theoretical analysis is the best and the most viable approach.

This review has not paid attention to the buckling and post-buckling theories relevant for stiffened shell structures. Therefore, to complement this review, further investigation is needed on the various proposed theories applied to different cases of buckling and post-buckling.

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