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Recent Advances in Analysis of Composite Stiffened Shells – A Review

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Abstract - Use of shell structures is increased in the modern aviation industry, submarines, commercial vehicles, ship hulls etc. As a result many new formulations for shell as well as stiffened shell elements are being developed. This paper is a review of many such finite element shell formulations. Initially, shells were developed using classical shell theory, which evolved to various shear deformation theories. Here, many such formulations are shown and their peculiarities along with their limitations are listed.

Index Terms - Shells, Static Analysis, Free Vibration.

INTRODUCTION

Shell structures are more widely used in recent years in fields such as robotics, aeronautical engineering, boats, submarines, and silos. The complicated shape of shells has made analysis challenging. Boundary conditions and geometry have an impact on shell analysis. Other aspects, such as support elasticity, size and fluctuating thickness, make shell analysis difficult and time-consuming. Despite these challenges, shell structures have long held a unique place among structural forms because they can provide a variety of benefits such as reduced weight, aesthetic appeal, and the capacity to cover huge areas without the use of additional columns.

Composites are a new category of materials born from the evolution of shell shapes and technology. These materials have a greater strength-to-weight ratio, a lower production cost, and a longer lifespan. These materials are used in the spacecraft, aviation, robotics, and naval industries, among others. They have a wide range of applications and can be adjusted to meet specific requirements, resulting in a material that can handle specific applications in harsh situations. Specific increased strength and stiffness, fatigue resistance, superior damage tolerance, and temperature tolerance are some of these severe situations.

Following the use of composites, a necessity to reinforce a specific area of the shell arose. According to general analysis, increasing the depth or size of a structure increases its strength. However, doing so in a shell would necessitate the considerable usage of materials that might not be required. There are several methods for increasing shell stiffness. Increasing the overall stiffness causes wastage of material and increases the dead load, rather than providing the structure with the requisite strength thanks to in-plane reactions provided by shell structures. The benefit of stiffening a shell is that it allows for a more cost-effective and lightweight design. While stiffening elements make only a small percentage of the total weight of the structure, they have a significant impact on its strength, stiffness, and stability. Aircraft structures, ship and boat hulls, bridge decks, and other industrial uses all utilise stiffened shell structures. Furthermore, due to their remarkable strength, stiffness, and lightweight capabilities, as well as their simplicity of manufacturing with complex shapes, the usage of modern composite materials has expanded in the above technical applications.

Many researchers have studied and reviewed shells over the years. As a result of the development of methods such as the finite strip method and finite element methods, various theories for shell analysis have arisen. Various elements have been used to study shells, their complexities, boundary conditions, and various stiffener effects on shells. Some researchers gave analytical results, while others a few relied on experiments, and still others provided combined analytical and experimental solutions .

LITERATURE REVIEW

Multirib isoparametric and multirib triangular finite elements have been developed by Mukhopadhyay M (1981). Elements are created in such a way that stiffeners can be arbitrarily placed and oriented well within the plate element. Theoretical accuracy is checked by solving various numericals with those of the lumped model prevailing at the time.

The element produced by Mukherjee was used Mukherjee and Mukhopadhyay (1988) for free vibration analysis of plates stiffened with eccentric stiffness. The authors introduced the facility such that the element can take care of irregular boundaries. The formulation also considers shear deformation and as a result can be used for thick as well as thin plates. Here, stiffeners are not needed to be placed necessarily on the nodal lines but can be placed randomly as per the requirement within the plate element. effects of various parameters such as shape, eccentricity of stiffener, stiffness due to torsion etc are studied on the natural frequencies of the stiffened plates.

Gateaux differential was used by Omurtag and Akoz (1992) used the to offer new innovative functionals for space bars and thin cylindrical shells with geometric and dynamic boundary conditions. These functionals can also be used to solve the conventional potential energy equation. The authors have applied a variational method to the functionals developed in this study, which plays a valuable part in the creation of mixed finite elements. Using Isoparametric finite element formulation, element matrices of cylindrical shells as well as space bars are formulated in the explicit form, including change in cross-sectional area. The eccentricity of space bars is taken into account when constructing finite element matrices. A rectangular shell element is four-noded and has 36 degrees of freedom, while a straight-circular two-noded space bar element has 24 degrees of freedom.

Stiffened composite plates for free vibration were researched by Mukhopadhyay et. al. (1992), using the finite element approach. For the required study, a quadratic isoparametric plate bending element was used. Stiffeners may be inserted arbitrarily in the plate element in the current formulation, and they are not required to follow nodal lines. Isoparametric components also benefit from the ability to include curved boundaries and incorporate transverse shear deformation. Varied shapes of laminates which are eccentrically stiffened, addressed for the analysis include rectangular, parallelogrammic, and circular shapes. Stiffener arrangement, cross-sectional characteristics, and angles are all different. The obtained natural frequencies were compared to those already available. There have also been parametric investigations.

Mukhopadhyay and Goswami (1994) used a Lagrangian isoparametric element having nine-nodes and the Heterosis element to study composite stiffened shells. Both elements have the benefit of the ability to include the effect of curved borders and shear deformation within the body. The stiffener does not have to be positioned at the nodal line because the formulation takes care of that. This allows for additional flexibility in modelling. These two parts have been used to investigate both concentric and eccentric stiffened composite shells. These two findings were compared. Different variables have been studied using parametric analysis.

Behaviour of stiffened plates in addition to shells with changing thickness not only in the stiffeners but also in the skin under several static as well as dynamic load conditions using a novel higher order randomly stiffened shallow shell finite element that is triangular and comprises of thickness dissimilarities is investigated by Sinha and Mukhopadhyay (1997). Any number of stiffening elements can be supported by the shell element, allowing the irregular mesh generation approach to be independent of the stiffener alignment in stiffened shell constructions. Both the stiffeners and the shell element have quadratic thickness variations. The undamped free vibration was done to ascertain the natural frequency of oscillation before analysing the dynamic response in the time domain. The numerical findings, when compared to known theoretical and/or practical data, demonstrate good agreement, even when utilising a coarse finite element mesh approach, for numerous issues involving un-stiffened plates and shells of changing thickness. A convergence test using element gridwork refinement was carried out for each investigation to show monotonic and highly fast convergence. Novel results for stiffened plates and shells investigations with varying plate/shell and stiffener thicknesses have also been reported.

Khare and Kant (1997) suggested a new finite element formulation having C0 continuity and is a member of the langrangian family of elements. It is a flat facet element which is based on a higher order displacement model. The element can be used for various shells ranging from thin to thick. It can also be used for composite laminated plates and shells reinforced by fibres. This philosophy avoids the application of shear correction coefficients and accommodates reasonable change of non-linear displacements inside the thickness of the shell. The discrete element selected has nine nodes and is a quadrilateral with two different degrees of freedom arrangements. One has five degrees of freedom while the other has nine degrees of freedom per node. The findings are then compared to the solutions obtained using nine noded first order elements as well as three dimensional precise answers and two dimensional thin classical theory solutions.

Layer-wise shell theory was used by Reddy and Kassegne (1998) for the various analysis such as vibration, pre-buckling as well as post-buckling stress calculations. The authors have reduced a three dimensional theory into a 2D theory by using the displacement field used in 3D as a function of surface displacement field as used in 2D along with a polynomial to describe 1D and interpolate the same, through the thickness of the shell. The authors here, have used 2D beam elements as stiffeners and they are modelled using layerwise framework. The stiffeners considered are of two types, circumferential and axial. Similar displacement fields are used for both, shells and stiffeners. Strain compatibility and force equilibrium are then taken into consideration between the shell and the stiffener to incorporate the contribution of stiffener in membrane stretching, bending and twisting stiffness of the laminated plate or shell.

For the first time, Chakraborty and Mukhopadhyay (2000) used the model update approaches to estimate the material property parameters of stiffened as well as unstiffened multilayered composite plates. The problem statement is described as a global reduction of the error function, which in turn is defined as the difference in mode shapes and undamped eigenvalues calculated by finite element modelling versus those measured empirically. An iterative gradient-based minimization approach is used to solve the parameter estimation problem, which can initiate with any arbitrarily chosen set of initial values. When compared to naked plates of similar manufacture, physical qualities, the position, and direction of stiffeners cause significant differences in modal properties. As a result, each of the stiffening plate difficulties is distinct. The methodology is shown to be strong as compared to those present in the literature at the time.

A three-noded curved-beam element is used for the stiffener and an eight-noded isoparametric element for shell element, were used by Prusty and Satsangi (2001) to perform static analysis of stiffened shells. The stiffener and shell parts both employ the same displacement function. The shell was examined using a modified technique, an upgrade on the degenerated shell notion. The stiffness matrix of the stiffener element is created regardless of the stiffener’s location along with direction inside the shell element. The stiffener's stiffness matrix is subsequently applied to each one of the shell element's nodes. The results of mathematical examples of shells having stiffeners positioning as eccentric and concentric have been investigated and compared to those found in the literature.

Ruotolo (2001) compared three theories namely Donnell's, Love's, Sanders', and FluKgge's thin shell theories in determining natural frequencies of cylindrical shells stiffened with stringers and rings whose influence happens to be spread throughout the full shell of the cylinder. It is shown that, in comparison to the other three theories, Donnell's theory delivers substantially erroneous results because of the huge increment in bending stiffness associated with rings. The work is completed by numerical results for aluminium and composite stiffened cylinders, as well as a comparison with results from a stiffened cylinder finite element model.

Carrera (2002) reviewed hypotheses along with Finite Elements for Composite, Anisotropic, Multilayered Plates and Shells. Three sections make up the paper. Part I considers 3D approaches, axiomatic and asymptotic two-dimensional theories, mixed and classical formulations, continuum-based methods, layer-wise and equivalent single layer variable descriptions, and equivalent single layer and layer-wise variable descriptions. In Part II, the author has looked at two–dimensional theories. Part III looked at Finite Element implementations. The possibilities for finite element advancements for multilayer plates and shells are first discussed. The approaches that consist of a particular use of finite element techniques, such as hybrid methods and global/local techniques, are examined alongside FEs based on the theories described in Part II. The use of finite elements to multilayered plates and shells, which were initially created for isotropic one-layered structures, is first described.

Aagaah and the others in 2003 discussed the effect of mechanical loads as well as the deformations that occurred in a composite laminated plate. The authors have used the third order shear deformation theory which falls in the classification of single layer theories, to get the linear dynamic equations of a laminated composite rectangular plate. The equations required for finite element analysis and various solutions such as distribution of stress and displacement at various positions on the plate are developed. The stress distribution and displacement are evaluated by subjecting the plate to a sinusoidal load and by solving the developed equations by Navier solution.

Doubly curved simply supported cross-ply laminated shells subjected to thermo-mechanical analysis are described by Khare et. Al (2003) using closed-form formulations of 2D higher-order shear deformation theories. The Sander's theory for shells having double curvature is included in the formulation. Various higher-order shear deformation theories have many similarities such as they all consider both transverse shear strains and stresses as well transverse normal strains and stresses, while the rest exclusively considers transverse shear deformation effects. A parabolic distribution, realistic in nature, of transverse shear strains through the shell thickness is postulated by the author. Uniform or sinusoidal temperature fluctuation is considered in the formulation across the surface and it linearly varies across the thickness. In laminated composite and sandwich shallow shells, numerical findings for thermal and mechanical load scenarios are presented. the closed-form solutions offered in the paper for laminated composite plates or shells are compared to 3D solutions available in the literature.

The theories for shear deformation of plates as well as shell are reviewed by Reddy and Arciniega (2004), and a coherent third-order theory for composite shells is suggested. From Stavsky to the present, the study of plate and shell theories is mostly a study of several ideas that can be used for modelling laminated shells, including shear effects. Subsequent to this explanation, the proposed theory is given a finite element formulation. On the inner and also the outer surfaces of the shell, the finite element is formulated such that it has seven displacement functions that meet the tangential traction-free criteria. The stress resultants are precisely computed using numerical integration of the laminate's material stiffness coefficients. For typical benchmark problems that involve isotropic and composite plates, as well as cylindrical and spherical shells, numerical examples are provided.

The linear analysis of laminated and anisotropic, moderately thick composite shells/shell-panels with double curvature is provided by Hossain et al (2004) using an updated finite element model. As the authors have based the model on the first order theory, Tensorial components are mixed interpolated to accommodate the effect of shear and membrane locking. In this research, the authors have specially attended to the spherical shells which are also rectangular in plan view. The least square smoothing approach is used to regularise the extensional and flexural stresses. The 3-D equilibrium equations are used to reconstruct the stress profiles for out-of-plane stresses. Numerical illustrations are used to validate the performance of the proposed element and the obtained results are found to be comparable to the solutions found in existing literature.

Ojeda et al (2007) described a novel method for analysing large deflections in isotropic as well as in composite arbitrarily oriented stiffened plates. The authors in this study used the virtual work principle to all of the continuum geometry where motion is described with total lagrangian description. The plate element is generated as a combination of an eight noded isoparametric element as the shell element stiffened with a three noded beam element. The formulation is done in such a way that any position of the stiffener within the shell element can be taken for analysis. To do so, the authors have computed the stiffness matrix of the shell and the stiffener element separately. The governing equations obtained during the study are then solved by using the Newton-Raphson method.

Using the lagrangian element developed earlier(Khare and Kant, 1994) Khare, Joshi, Choubey (2008) developed stiffened composite shell element based on first order shear theory and analysed it. The stiffened element was used for thin plates/shells extending to moderately thick plates/shells and found to perform satisfactorily compared with available literature.

Static analysis of laminated composite plates by developing a new mixed finite element model is presented by Moleiro et al (2008). The formulation of the current study is based on the least-squares variational principle, which serves as an alternate method to mixed weak form finite element models. The current model uses the first-order shear deformation theory as an independent variable, together with generalised displacements and stress resultants. The mixed model is created utilising full integration and equal-order C0 Lagrange interpolation functions with high p-values. The governing equations for the mixed model are obtained as positive definite and symmetric system of algebraic equations. Illustrations having variety such as boundary conditions, changing shell to stiffener ratio demonstrate the capacity of the current model. In this paper, the authors have found that the shear locking remains unaffected when, the model under study is used.

Osama (2009) examine and synthesise engineering work done for all of the applications of stiffened plats and shells. The first section goes over the numerical, analytical, and orthotropic plate methodologies that have been established for stiffened plate and shell analysis. Each method's structural idealisation, theoretical foundation, and merits are also explored. The paper's second section examines the design philosophies that have been created to forecast the eventual strength of these structures. The impact of numerous structural performance characteristics, such as stiffener profile, geometric and material flaws, and so on, is explored. The optimization approaches for reducing the structure's weight are also discussed. The publication serves as a comprehensive and one-of-a-kind "reference manual" for stiffened plate applications of all kinds.

The authors Yadzani et al (2009) describe the findings of an experimental research typically based on the bending behaviour of thin-walled GFRP cylindrical shells. Using a newly constructed filament winding machine, the specimens were made from continuous glass fibre. Under quasi-static axial loads at room temperature, the buckling behaviours of unstiffened shells and stiffened shells with various stiffener profiles such as triangular, lozenge, and hexagonal grids were investigated. All specimens first experienced general buckling and barrelling under the applied force because of the thin wall of the shells. All specimens were observed for Local buckling mode after this general buckling injury. The critical buckling stress for shells with hexagonal and triangular grids was higher in the experiments, while the critical buckling load for unstiffened shells and stiffened shells with lozenge grids was substantially lower. The authors found that for very thin shells, unstiffened shells performed better and had a higher bucking load as compared to other shells.

To perform linear static analysis of laminated structures, Alpay et. al. (2010) proposed a three-node shell element with six degrees of freedom per node. The element is formulated in such a way that it has one drilling degree of freedom which handles rotation and the rest of the element is a C0 Mindlin-type element. Because of such formulation, modelling folded structures that basically show two types of behavior such as in-plane bending and transverse bending. The authors have attempted to formulate the element such that the shell-stiffener connection also behaves as a folded plate and as a result they have achieved comparable accuracy. Convergence and validation is done by solving various numerical problems as available in the literature.

An attempt to establish dominance of higher-order shear deformation theory (HSDT) over and above the first-order shear deformation theory (FSDT) for various analysis involving laminated composite stiffened plates is demonstrated efficiently by authors Bhar et al. (2010). For the static as well as free vibration analysis of the plates, an HSDT element having C0 continuity is developed for the study. Displacements fields for all the elements, the plate as well as the stiffener, are computed using Taylor series expansion. Various examples are solved using HSDT and FSDT and it is established by the authors that use of HSDT for such analysis shows better results as compared to FSDT.

Moleiro et al. (2011) constructed a layerwise finite element model using a mixed least-squares formulation to carry out the static analysis of multilayered composite plates. As independent variables are extensively used in the study by the authors, it requires a layerwise variable description of displacements, transverse stresses, and in-plane strains. Due to compatibility and equilibrium reasons, the mixed formulation allows for complete and a priori fulfilment of the known C_z^0 conditions, which refer to the zig-zag form of displacements in the thickness direction and the interlaminar continuity of transverse stresses. This is in contrast to layerwise displacement-based models, which frequently fail to account for the interlaminar continuity of transverse stresses a priori. Furthermore, as opposed to mixed weak form models, the mixed least-squares formulation leads to a variational unconstrained minimization issue, where the finite element approximation spaces can be chosen separately. In comparison to three-dimensional elasticity solutions and other finite element results available in the literature, numerical examples are provided to examine the layerwise mixed least-squares model prediction capabilities. Most importantly, the current model is demonstrated to be insensitive to shear-locking and can produce accurate findings in very excellent agreement with three-dimensional solutions.

Zhang and Chen (2011) developed a triangular stiffened composite plate/shell element. The authors have based the element on Mindlin-type shear deformation theory. The newly formulated element is used to investigate advanced grid stiffened (AGS) structures. To meet the compatibility of displacement at the joint of the shell and the ribs, the rotations of the shell are interpolated with those of the ribs. There are no restrictions on the amount, position, or alignment of the stiffeners when creating a finite element mesh. The numerical results suggest that it works, especially for AGS structures with more ribs. Stability assessments for an isogrid cylindrical shell as well as an ortho-grid plate are also available.

Kuriakose et al. (2012) used ANSYS, to investigate the linear behaviour of laminated composite shells under static stress by changing various parameters regarding the shells. The parameters include thickness of laminate, orientation of the fibres, the sequence in which the laminates are stacked, strength of each fibre, and also the radius-to-thickness ratio. For anti-symmetric designs, the authors found that the deflection does not change beyond four layers, and deflection is unchanged by the lamination sequence for that similar angle of fibre origination. Non-dimensional deflection is reduced as material anisotropy and included angle rise, whereas it is increased when the radius-to-thickness ratio increases.

Vanam et al (2012) looks at the static analysis of an isotropic rectangular plate as well as a variety of load applications and boundary conditions. For Finite element analysis of an isotropic rectangular plate, the master element is considered as a four-noded quadrilateral element. The findings produced using MATLAB are in good agreement with the results obtained using the traditional method - exact solutions. Later on, the identical structure was analysed using the ANSYS finite element analysis programme. This work is useful for collecting results not only at node sites but also across the full rectangular plate's surface. Finally, the findings of the FEA numerical analysis were compared to the ANSYS results using the traditional method - exact solutions. The findings of finite element analysis and ANSYS simulation are in close correspondence with the outcomes of exact solutions from the classical method, according to numerical results. When the plate is subjected to various loading and boundary conditions during this analysis, the ideal thickness of the plate is determined.

Kolvik (2012) studied the theories of plate analysis developed by Shi and Reddy. The author has made a successful attempt in formulating a novel higher order shear deformation theory. Kolvik investigated the buckling behavior by generating the governing equations using the variational technique. The solution of these equations was reached at by Navier's method. The solutions obtained, are thereby compared with those obtained by using shi and reddy's theories as well as some other higher order theories. The author has found comparable results using his newly developed unified higher order shear deformation theory.

A simple first order shear deformation theory for laminated composite plates is presented by Thai and Choi (2013). The authors have taken their inspiration from the flaws of the previous shear deformation theories and have managed to develop the recent theory with as less as four unknowns. The present theory is in a way much similar to the classical laminate theory if the aspects such as boundary conditions, equations which describe the motion and expressions for stress resultants. The governing equations and the boundary conditions are taken such that they follow Hamilton's variational principle. Simply supported laminated plates, with their ply orientation as cross-ply and angle-ply have been investigated through the present model. Authors have achieved acceptable relevance with the values as given by the exact 3D solutions.

Viola et al. (2013) developed a 2D Higher-order Shear Deformation Theory (HSDT). The use of this theory is done to carry out the static analysis of Laminated composites with double curvatures. Theory adopted in this study by the authors depends upon generalised nine-parameters. The authors have shown 3-D stress recovery using equilibrium equations. Strains as well as the stresses obtained by solving these equations are then corrected so as to satisfy the boundary conditions for top and bottom fibres. Solution to the equilibrium equations is obtained by the generalised quatrature technique (GDQ). The analysis of six different types of structures including plates, having rectangular as well as annular geometry, along with, cylindrical and spherical shells, catenoidal shells are also solved followed by solution for an elliptic paraboloid. The results are stated and plotted and it is observed that they are in fine comparison with results available in the literature.

Desai and Kant (2015) use higher order shell theory to do numerical analysis for thick circular cylindrical shells. The authors have derived all the equations using a different coordinate system which is orthogonal curvilinear. Along with this coordinate system, the study also includes summation of extra quadratic and cubic terms, not only in the in-plane displacement but also in the transverse displacement. The equations are developed using a variational principle given by Reissner. By the use of this variational principle the authors have managed to reduce a 3-D elasticity to 2-D. All the equations obtained as differential equations of the first order were solved using segmentation technique and results are obtained.

Shreehari (2017) computes and analyses composite plate responses using first and higher order shear deformation theories. This research creates a finite element formulation for the analysis of laminated composite plates. The current study delves into the formulation that makes programming simple even for a novice in this subject. The mathematical formulation and MATLAB code for First Order Shear Deformation Theory (FSDT) and Higher Order Shear Deformation Theory (HSDT) are complete. The findings were compared to the existing literature. A parametric research was also conducted to further explain the differences in findings produced from both the FSDT and the HSDT.

A thorough static and dynamic analysis formulation for doubly curved shells, is described by Kant and Punera (2017) utilising twelve middle surface displacement parameters as proposed in the higher order shear and normal deformation theory (HOSNT). Two dimensional theories were required because of the difficulties that came to light in establishing three dimensional theories. The authors have tried to accommodate transverse shear strains and the normal strains as well by accepting dynamic terms for inertia and the related higher order expressions. In the study, variational principle is used which in-turn uses energy minimization to formulate the governing equations and defining boundary conditions.

Dynamic stiffness and damping constant can be determined in a very reliable and a non-destructive way by modal testing. The purpose of Nazari etl al (2019) is to use experimental and numerical techniques to study the modal response of circular cylindrical shells stiffened with Fiber Metal Laminates (FML). Three types of FML-stiffened shells are manufactured for this purpose using a specially designed process, and their mechanical properties are determined using a burning inspection. Modal experiments are used to study the vibration and damping characteristics of the FML-stiffened shells. Authors have taken the aide of ABAQUS program to construct a 3D finite element that can effectively predict the modal properties of FML-stiffened circular cylindrical shells having free ends at all the supports. Authors have stated and compared the numerical and experimental data, and there is a high level of agreement. This is the first study of modal analysis of circular cylindrical shells stiffened with FML.

Shreadha and Pany (2020) examine the literature on composite flat panel, curved panel, and cylindrical shell static, free vibration, and buckling analyses. This study also summarises design guidelines for laminates, the laminate testing technique, and estimates the cost connected with the mechanical properties such as comparing the laminates with the already available materials such as metals. The authors are of the view that various environmental effects like effect of temperature and moisture are also included in the classical laminate theory.

Liu et al (2020) proved that curvilinearly stiffened plates can outperform typical straight-line stiffened plates in terms of mechanical performance. As the thickness of the plate reduced, the discrete shear triangle element was proposed by using discrete shear limitations on every side to avoid the shear locking problem in the modelling of stiffened thick plates as stated very clearly by Reissner-Mindlin theory. The plate is stiffened using the discrete shear triangle element, whereas the curvilinear stiffeners are stiffened using the Timoshenko beam theory. The FE equations are generated from the plate's displacement interpolation function and the plate-stiffened interfaces' displacement compatibility criteria. The plate and stiffener are represented independently in the current study, allowing nodes of the stiffener element to avoid overlapping with those of the plate's shell-element. A freshly developed modelling procedure is used to investigate all kinds of behavior namely the statics, vibration, and buckling behaviour of curvilinearly stiffened plates. The authors support their innovative findings with experimental and numerical studies on the stiffened plates. The authors have achieved acceptable accuracy in the static as well as the dynamic analysis of not only the thin plates but also thick plates. The authors have managed to do so by using fewer numbers of shells.

Huang and Qiao (2020) developed a new method to investigate the nonlinear stability behaviour of rotationally-restrained stiffened laminated composite shallow shells with double curvature and imperfection. The shells under study are subjected to in-plane shear and compression loads. The semi-analytical method developed in this work is such that, it can carry out analysis for all the types of stiffened shells, including concentric and eccentrically stiffened shells having variations in stiffness. If the shell has varying stiffness along each curvature, then for such an instance the authors have applied the Heaviside function distinctly to be able to accommodate the change in stiffness. Two methods are applied by the authors to solve the shell problems. Here, Galerkin method is resorted to, so that it can solve the non-linear governing equations and the Riks method obtains the snapping phenomenon that occurs in the stiffened shells. Various parameters such as curvature of radii, stiffener thickness and orientation, the amount of imperfection, whether edge is restrained to rotate, etc are studied and their effects are listed.

Thermoelastic analysis of sandwich cylindrical/ spherical shells and laminated composite utilising fifth-order shear and normal deformation theory is by Shinde and Sayyad (2020). The fact that the current theory takes into account both transverse and normal deformations is a noteworthy feature. Virutal work is taken into consideration so as to generate governing equations which are variationally consistent as well as cater to traction free boundary conditions. The authors have used the Navier's solution to carry out the static analysis from the governing equations.. A mechanical/ thermal load is applied to the shell's upper surface in a sinusoidal pattern. As the thickness of the shell grows, so does the heat load. Alternative higher-order models and 3D elasticity solutions are compared to the current results whenever possible.

Panin and Semenov (2020) describe the development of non-linear deformation of reinforced concrete shell structures. In the form of a complete potential deformation energy functional, there is a mathematical model of deformation. The model is established on the Kirchhoff–Love hypothesis and permits the consideration of shell to be reinforced with stiffeners. From the concave side, an orthogonal network of stiffeners supports the shell. The structure is loaded externally with a uniformly distributed loaded. The Ritz approach is applied by the authors to the functional to reduce the variational issue to a set of nonlinear algebraic equations. The problem is then solved using iterative methods for each load value. The strength and stability of shallow double-curvature shells with a rectangular planform are investigated. Deflection curves based on load are supplied. All of the results are presented in terms of dimensionless parameters. For concrete strength analysis, the Mohr–Coulomb criterion was utilised, and for stability analysis, the Lyapunov criterion was used. The number of stiffeners used to reinforce the shell influences the stress values that result. When the relationship between stresses and deformations is curvilinear, physical non-linearity of concrete is taken into consideration, deformations of shells rise in comparison to the linear-elastic solution. Stress redistribution over the shell field was also demonstrated when nonlinearity was taken into account.

Various shear deformation theories for laminated composite plates have been developed over years. Mahji and Mahato (2020) reviewed the step by step development and application of these theories. Primarily talks about the theoretical finite element models based on these theories. The entire review is categorized in single layer laminate and layerwise laminate theories. Theories starting from first order shear deformation theory in the first category to the latest higher order shear deformation theory. While the second category ranges from the classical laminate theory to the newly developed discrete-layer and zig-zag laminate theories.

Laminated composite stiffened cylindrical (LCSC) panel is studied for non-linear dynamic buckling behavior and collapse, when it is exposed to rectangular in-plane pulse stress and sinusoidal pulse stress by Keshav et al (2021) by using a finite element framework. The authors have used four distinct failure theories to look at symmetric balanced laminates. The laminates considered in the study are cros-ply as well as angle ply. An attempt has been made to calculate the panel's first ply failure load and its order is checked with the non-linear dynamic buckling. The new mathematical formulation proposed is used to converge and validate the results, which are then compared to those found in the literature. Effects of various factors like loading function, loading time, skin and stiffener ply orientation, and stiffener aspect ratio are studied in depth over the non-linear dynamic buckling of the LCSC. The authors have found that the load required for dynamic buckling of angle ply panel (45°/-45°/-45°/45°) is lower then the unstiffened panel as calculated on application of a rectangular pulse when the aspect ratio of stiffener is kept upto 8. When the aspect ratio is kept under 4, stiffened panels buckle at a lower load as compared to unstiffened panels on effect of rectangular pulse.

External pressure is applied on cylindrical shells which are ring stiffened. Along with the local shell buckling and torsional buckling of stiffener, the authors Shiomitsu and Yanagihara (2021) also discuss the ultimate strength over and above the behavior at collapse for the shells under study. The impact of initial deflection form on final strength has not been fully explored in previous research. Furthermore, there is yet to be an explanation of the collapse behaviour and a theoretical formulation based on it. Hence, the influence of initial deflection shape, is studied by taking the eigen modes, which are calculated using elastic buckling eigen-value analysis. For the ultimate strength the authors, in this study have used the non-linear finite element method to solve 432 models of cylindrical shells having different sizes. Going further, to notice the behavior at collapse, the modes linked with collapse are classed into five different categories based on whether the collapse is due to shell buckling or torsional buckling or a combined effect of torsional and shell buckling. The authors have derived their own formulae for strength, stress reaches yield stress level along with the equation for elastic buckling strength. The two equations are then combined to arrive at a novel slenderness ratio which is used to build theoretical formulations for ultimate strength.

Conclusion

The present paper reviews various papers starting from the time when there were no computers and the finite elements used to have so many degrees of freedom so as to carry out analysis. The paper is a consolidated review of the papers establishing development of various theories over the time starting from the first order theory to the latest higher order shear deformation theory. It also accounts various shell elements used for static as well as free vibration of laminated plates and shells and has tried to cover stiffened shells as well.

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