

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Extensive use of metals and composite materials in the fields of aerospace, automobile, construction biomechanics has led to research on the stability of structures composed of these materials. Although the investigation pertains to the loss of stability in composite plates and cylindrical panels due to in-plane pulse loads, a thorough literature survey in the field of stability is necessary. To this end, the loss of stability due to static loads, pulsating loads and pulse loads has been carried out. The studies on plates, plates with cutouts, stiffened plates, cylindrical panels, cylindrical panels with cutouts and stiffened cylindrical panels are considered. Due consideration is given to the type of loading, boundary conditions, type of analysis and materials. This chapter is divided into the following subsections:

- Static Buckling
 - Plates (isotropic plates, composite plates, plates with cutouts and stiffened plates)
 - Cylindrical Panel (isotropic cylindrical panels, composite cylindrical panels, cylindrical panels with cutouts and stiffened cylindrical panels)
- Parametric Instability
 - Plates (isotropic plates, composite plates, plates with cutouts and stiffened plates)
 - Cylindrical Panel (isotropic cylindrical panels, composite cylindrical panels, cylindrical panels with cutouts and stiffened cylindrical panels)
- Stability due to Suddenly Applied In-Plane Pulse Loads (isotropic plates, composite plates, plates with cutouts and stiffened plates isotropic cylindrical panels, composite cylindrical panels, cylindrical panels with cutouts and stiffened cylindrical panels)

- Failure Theories (Composite plates and cylindrical panels)
- Need for Further Research
- Objectives of the Present Study

2.2 Static Buckling

In this section, the studies related to static buckling of plates and cylindrical panels are presented. First, the investigations related to static buckling of plates, plates with cutouts and stiffened plates are presented followed by the static buckling analysis of cylindrical panels, cylindrical panels with cutouts and stiffened cylindrical panels.

2.2.1 Plates

In this section, the studies related to the static buckling analysis of isotropic plates, composite plates, isotropic plates with cutouts, composite plates with cutouts, isotropic stiffened plates and isotropic composite plates by various authors are presented. The investigations concerning analytical methods, numerical methods and experimental methods are considered.

The loss of stability of plates due to static in-plane loads has been dealt with by many researchers. These studies have considered both isotropic and composite plates subjected to uniaxial and bi-axial loads. Many authors have considered the various complexities such as boundary conditions, non-uniform loads, presence of cutouts and presence of stiffeners in the plates. The earliest studies on the problem of static buckling of plates were performed using analytical methods, and due to complexities in calculating the exact solution, the authors proposed approximate solutions for the static buckling analysis. The problem of static buckling of a plate was first studied by Bryan (1890). The author utilized the energy principle to evaluate the loss of stability. Taylor (1933) studied the static buckling of isotropic plates clamped at all four edges and subjected to bi-axial loads using an analytical method. Budiansky (1948) investigated the static buckling of isotropic simply supported long plates, supported by rigid posts using an analytical method. Stowell (1948) studied the buckling of simply supported and clamped plates Libove *et al.* (1949) calculated the static buckling of simply supported isotropic plates, subjected to non-uniform compressive stresses using Rayleigh-Ritz method. An

approximate method based on energy principles to calculate the buckling of isotropic plates subjected to uniform stress was presented by Handelman and Prager (1949).

Moreover, the theories and the experimental results of static buckling analysis of isotropic plates were compiled by Gerard and Becker (1957a). The authors presented charts for non-dimensional static buckling load for plates subjected to various boundary conditions. Bauer and Reiss (1965) investigated the non-linear buckling of an isotropic plate using a numerical method. Benoy (1969) presented the results of the static buckling analysis of isotropic plates subjected to parabolic loading using an analytical method and compared the results obtained from the finite element method.

With the development of the finite element method, many authors have proposed plate elements in the finite element framework for conducting the static buckling analysis. A plate element was proposed by Carson and Newton (1969) requiring a coarse mesh to investigate the static buckling of isotropic plates using the finite element method. Smith and Sridharan (1978) investigated the static buckling of plates supported at the ends using rigid diaphragms using the finite strip method and reported better computational economy when compared to the finite element method. Dawe and Roufaeil (1982) presented the results of the static buckling analysis of isotropic plates using a numerical method with the incorporation of the transverse shear effect in the mathematical formulation. Senthilnathan *et al.* (1987) investigated the static buckling of isotropic shear deformable plates using modified higher-order theory. Wang *et al.* (1994) presented the results of the static buckling analysis of plates of various shapes using Rayleigh-Ritz method and reported that the shear deformation effect decreases the buckling load in plates. Optimization techniques are also considered for the thickness of the plate for a given volume to maximize the static buckling load (Manickarajah *et al.*, 1998).

Furthermore, the static buckling analysis of long isotropic plates supported by two clamped edges and subjected to biaxial loading has been performed using a numerical method (Audoly *et al.*, 2002). Eisenberger and Alexandrov (2003) presented the results of the static buckling analysis of isotropic plates with variable thickness using numerical method. Purbolaksono and Aliabadi (2005) studied static buckling of isotropic plates using a numerical method. The authors presented the formulation of shear deformable plates and reported results for various boundary conditions and loading conditions. Ruocco *et al.* (2011) investigated the static

buckling of isotropic plates for various boundary conditions using an analytical method by assuming a combination of trigonometric and polynomial displacements to solve the buckling problem. *Ádány et al.* (2018) proposed a method based on constrained finite strip method in the framework of the finite element method requiring rectangular discretization of the plate for the static buckling analysis.

With the wide use of composite materials in various sectors, the buckling of plates made of composite materials has been investigated by many researchers. Ashton and Love (1969) demonstrated the applicability of reduced bending stiffness matrix for analyzing the static buckling of unsymmetrically laminated plates, clamped edges. Holston (1970) presented the results of the static buckling analysis of orthotropic plates with one edge free and rest simply supported using an analytical method and presented an approximate equation for calculating the static buckling load. A detailed literature survey on shear buckling of isotropic and orthotropic plates was presented by Johns (1971). Jones (1973) presented an exact solution based on classical plate theory for static buckling and vibration of simply supported, laminated cross-ply plates and reported that plates with a large number of layers do not guarantee better performance.

Furthermore, a very exhaustive literature survey of static buckling and post-buckling of laminated composite plates and shells has been presented (Leissa, 1985; Leissa, 1987) for structures with various boundary conditions and plate orthotropy. Leissa (1985) also compiled charts of analytical and experimental results. Chia (1988) discussed various parameters that affect the geometric nonlinear behaviour of composite plates. Reddy and Khdeir (1989) investigated the vibration and static buckling of laminated composite plates using the finite element method using three plate theories and reported that the natural frequencies and static buckling loads predicted by classical plate theory were conservative. Narita and Leissa (1990) studied the static buckling of laminated composite plates subjected to various types of loading conditions using a numerical method.

Additionally, a triangular element based on higher order theory was proposed by Chakrabarti and Sheikh (2003) for the static buckling analysis of laminated composite plates. Setoodeh and Karami (2003) studied the static buckling of laminated composite plates with elastically restrained edges using the finite element method based on layer-wise laminated plate

theory. Hu *et al.* (2003) studied the static buckling of a composite plate subjected to parabolic loads in the longitudinal and transverse direction using the Rayleigh-Ritz method. The authors reported that the static buckling load for plates subjected to parabolic loads were lower than the static buckling loads when subjected to uniform loads. Shufrin *et al.* (2008) investigated the static buckling of laminated composite plates subjected to a combination of shear, compressive and tensile loads using a semi-analytical method based on classical plate theory.

Recently, the results of the static buckling analysis of isotropic and orthotropic plates using an analytical method based on refined plate theory without the requirement of shear correction factors were presented by Kim *et al.* (2009). Kuo and Shiau (2009) investigated the static buckling of laminated composite plates with variable fibre spacing using the finite element method. Ferreira *et al.* (2011a) reported the results of the static buckling analysis of laminated composite plates using an analytical method based on third-order shear deformation theory and radial basis function. Ferreira *et al.* (2011b) investigated the static buckling of laminated composite plates using an analytical method based on first-order shear deformation theory and radial basis function. Hayman *et al.* (2011) reported details of collaborative work as a part of MARSTRUCT program on the static buckling analysis of laminated composite plates conducted using experimental and finite element method. Sayyad and Ghugal (2014) studied the static buckling of isotropic and composite plates using an analytical method based on trigonometric shear and normal deformation theory.

The requirement of providing cutouts in plates has led to some studies in the static buckling of isotropic plates by some authors. Levy *et al.* (1947) investigated the static buckling of isotropic plates with circular reinforced cutout using a numerical method. Chow and Narayanan (1984) investigated the static buckling of isotropic plates with circular and square cutouts using the finite element method. Brown *et al.* (1987) studied the static buckling of an isotropic plate with a rectangular cutout at the centre subjected to biaxial, uniaxial and shear loading using the finite element method. Nemeth (1991) reported results of an experimental study conducted on static buckling of isotropic plates with a cutout at the centre of the plate. Ko (1998) investigated the buckling of an isotropic cylindrical panel with circular and square cutouts with various boundary conditions using a computer program based on the finite element method. Komur and Sonmez (2008) reported the results buckling analysis of plates with circular cutout located

at various locations in the plate using the finite element method and suggested that the location of cutout should not be near the ends of a rectangular plate. Moen and Schafer (2009) reported simplified expressions for calculating the buckling load of isotropic plates with single or multiple cutouts based on classical plate theory. Cheng and Zhao (2010) investigated the buckling of isotropic plates with strengthened circular cutouts using the finite element method. Yao and Rasmussen (2012) studied the buckling and failure modes of isotropic plates with single or multiple cutouts of various shapes using the finite strip method. Helbig *et al.* (2016) studied the buckling of steel plates with various cutout shapes using the finite element method and presented limit curves for avoiding buckling.

Moreover, an approximate solution for the static buckling problem of a laminated composite plate with a circular cutout at the centre has been proposed by Nemeth *et al.* (1986). Nemeth (1990) experimentally investigated the static buckling and post-buckling of laminated composite plates with central circular cutout. Srivatsa and Murty (1992) presented the results of static buckling analysis of laminated composite plates with a circular cutout at the centre of the plate using the finite element method. Baba (2007) presented the results of buckling analysis of a laminated composite plate with central cutout experimentally and using the finite element method. Baba and Baltaci (2007) studied the static buckling of laminated composite plates with cutouts at the centre of the plate for various boundary conditions. Komur *et al.* (2010) studied the static buckling of a laminated composite plate with elliptical cutout oriented at various positions using the finite element method. Ghannadpour *et al.* (2010) investigated the buckling of laminated composite plates with central circular and elliptical cutout using the finite element method. Ovcy and Fazilati (2012) reported the results buckling analysis of a laminated composite plate with central cutout using the finite strip method. Erkliğ and Yeter (2012) investigated the buckling of laminated composite plates with various cutout shapes using the finite element method.

Additionally, the static buckling of isotropic plates with various geometries of stiffeners has also been investigated. Budiansky and Seide (1948) studied the static buckling of simply supported long plates with many stiffeners in the perpendicular direction to the applied loads using an analytical method. Seide and Stein (1949) presented charts for static buckling of simply supported isotropic plates with various stiffener configurations. The effect of the

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slenderness of stiffeners on the static buckling of stiffened plates was investigated by Sridharan (1983) using the finite strip method. Stroud *et al.* (1984) investigated the static buckling of isotropic plates stiffened with blade, hat and Z stiffeners subjected to in-plane compression and shear using various well-known computer programs. Steen (1989) studied the static buckling and post-buckling of stiffened plates using an analytical method. The authors neglected the local plate or stiffener buckling for the study. Mukhopadhyay and Mukherjee (1990) proposed an iso-parametric plate element for calculating the static buckling of stiffened rectangular plates. Bedair and Sherbourne (1993) proposed a general expression for calculating the static buckling load of a stiffened plate subjected to non-uniform in-plane loads. Optimization technique has also been used to calculate the buckling load of isotropic plate stiffened orthogonally and longitudinally (Bedair, 1997).

Furthermore, Sheikh *et al.* (2002) investigated the various modes of buckling in a stiffened isotropic plate and also reported parametric study on tripping mode of failure. Srivastava *et al.* (2003a) reported the results static buckling analysis of isotropic plates subjected to partial edge loads using the finite element method. Peng *et al.* (2006) calculated the static buckling load of a stiffened isotropic plate using meshfree finite element method based on first-order shear deformation theory. Ni *et al.* (2015) reported a review of literature on static buckling and post-buckling of isotropic stiffened plates from 2000 till 2012. Sadamoto *et al.* (2017) proposed a shell element for meshfree analysis of static buckling of a stiffened plate. Graciano and Mendes (2014) studied the static buckling of an isotropic plate with T shaped stiffener using the finite element method and reported results of effect if initial imperfection in the plate on static buckling of the stiffened plate.

Stiffened composite plates have been considered by some authors for buckling analysis. The effect of imperfection on buckling of a laminated composite plate with blade stiffener using an analytical method has been studied by Stroud *et al.* (1977). The authors stipulated that the initial imperfection should be incorporated in the design if, bow type imperfection was encountered. Stroud *et al.* (1984) presented the results of static buckling analysis of laminated composite plates stiffened with stiffeners of various geometries subjected to in-plane compression and shear loads. Loughlan and Delaunoy (1993) investigated the static buckling of laminated composite stiffened plates using the finite strip method and reported results of

partial edge loading and shear loading. Nagendra *et al.* (1994) studied the buckling of stiffened composite plates and attributed the variation in experimental and analytical results to the geometric imperfections in the stiffened plates. An optimization technique for optimization of the skin and stiffener lay-up, stiffener shapes and geometric dimensions based on genetic algorithm was reported by Vescovini and Bisagni (1993). Kumar and Mukhopadhyay (1999) proposed a triangular element for calculating the static buckling of a stiffened laminated composite plate using the finite element method for parallel and perpendicular stacking in the stiffener.

Furthermore, a triangular element for calculating the static buckling and natural frequency of stiffened plates was proposed by Rikards *et al.* (2001). Guo *et al.* (2002) developed a layer-wise formulation for studying buckling of laminated composite stiffened plates by modelling the plate with degenerated shell element and stiffener with beam element. Stamatelos *et al.* (2011) investigated the static local buckling of a laminated composite stiffened plate for various boundary conditions using an analytical method. Huang *et al.* (2015) proposed modelling technique for the finite element method to study the buckling of a composite plate with grid stiffeners. Experimental investigation on the static buckling analysis of stiffened plates was conducted by Kolanu *et al.* (2016). The authors also monitored the surface strain and displacement in the stiffened plate using digital image correlation technique.

Summary

It is observed that the static buckling behaviour of plates made of isotropic and composite materials has been investigated thoroughly. The effect of various parameters like geometry, material, cutouts and stiffeners have also been considered by the authors. Analytical, Experimental and Numerical methods have been considered for understanding the static buckling behaviour of plates.

2.2.2 Cylindrical panel

In this section, the studies related to static buckling of cylindrical panels are presented. cylindrical panels with and without cutouts made of isotropic materials, composite materials are considered. Also, studies on stiffened isotropic and composite panels are summarized.

The studies related to the static buckling of isotropic cylindrical shells (complete cylinder) are plenty. However, studies on buckling of cylindrical panels (also called curved plates) are few. Kromm (1939) investigated the static buckling of long isotropic cylindrical panel under the combined action of axial and shear loads. Gerard and Becker (1957b) studied the static buckling of isotropic cylindrical panels and reported charts for various loading conditions. Dawe (1977) presented the results of static buckling analysis of isotropic cylindrical panels subjected to biaxial loading using the finite strip method. Guggenberger *et al.* (2000) reported the results of the static buckling analysis of isotropic cylinder using the finite element method. The authors considered linear and non-linear behaviour for a part of the cylinder.

Moreover, the results of the buckling analysis of long composite cylindrical panels with various boundary conditions have been presented by Viswanathan *et al.* (1974), using an analytical method. Sinha and Rath (1975) presented the results of an analytical study on the static buckling of simply supported cross-ply composite cylindrical panels. Wilkins (1975) studied the static buckling of laminated composite cylindrical panels by using exhaustive experiments and reports results of the effect of ply orientation and radius of curvature of the panel. The static buckling analysis of plates and cylindrical panels was performed experimentally and using the finite difference method by Bauld and Khot (1982). Becker *et al.* (1982) reported the results of the static buckling analysis of cylindrical panels experimentally and described the procedure for fabrication and testing of the panels. Zhang and Matthews (1983) studied the static buckling of laminated composite cylindrical panels subjected to in-plane compression and shear using an analytical method.

Furthermore, the results of the static buckling analysis in the finite element method framework have been reported by Saigal *et al.* (1986) for composite cylindrical panels with imperfections and geometric non-linearity. Jun and Hong (1988) investigated the buckling of composite cylindrical panels using the finite element method with the incorporation of geometric non-linearity. Cali and Esposito (1993) investigated the buckling of a composite cylindrical panel using the finite element method and reported linear buckling analysis results. Kweon and Hong (1994) studied the buckling and post-buckling of laminated composite cylindrical panels using the finite element method. Kim and Voyiadjis (1999) investigated the static buckling and post-buckling of laminated composite cylindrical panels using the finite

element method considering geometric non-linearity in the panel. Arciniega *et al.* (2004) presented the results of the buckling analysis and post-buckling analysis of composite cylindrical panel using an analytical method based on third-order shear deformation theory. Hilburger *et al.* (2005) studied the static buckling of composite cylindrical panel subjected to initial stress, induced from test fixtures using the finite element method. Adali and Cagdas (2011) investigated the static buckling of a simply supported composite cylindrical panel using the finite element method and reported optimal stacking scheme for buckling. The results of the static buckling analysis of skew composite cylindrical panels using the finite element method are presented by Srinivasa *et al.* (2014).

Additionally, the static buckling of composite cylindrical panels with cutouts is analysed by a few authors. Palazotto and Tisler (1988) calculated the static buckling load of a laminated composite cylindrical panel with square cutout using the finite element code – STAGSC-1. Dennis and Palazotto (1990) investigated the static buckling of composite cylindrical panel with a square cutout at the centre of the panel using the finite element method. Madenci and Barut (1994) presented the results of the static buckling and post-buckling analyses of a composite cylindrical panel with circular and square cutouts using the arc-length method. Noor *et al.* (1996) calculated the static buckling of a laminated composite cylindrical panel with a circular cutout at the centre using the finite element method. The static buckling of a quasi-isotropic cylindrical panel with circular cutout was checked experimentally and by the means of the finite element method (Hilburger *et al.*, 2001). Dash *et al.* (2004) reported the results of static buckling analysis of a composite cylindrical panel with a square cutout at the centre using the finite element method. Hu and Yang (2007) reported the results of static buckling analysis of composite cylindrical panels with a circular cutout at the centre of the panel using the finite element method and presented the optimization technique to maximise the static buckling load using stacking sequence in the panel.

Apart from these, the buckling analysis of stiffened isotropic cylindrical panels has been undertaken by some authors. Schildcrout and Stein (1949) reported curves and tables for the buckling of stiffened simply supported cylindrical panels subjected to uni-axial loads. Arnold and Parekh (1987) presented an analytical method for calculating the buckling load of an isotropic cylindrical panel subjected to compressive loads and shear loads. Tvergaard and

Needleman (2000) investigated the static buckling of isotropic stiffened cylindrical panels using a numerical method. Choi *et al.* (2009) investigated the buckling behaviour of isotropic stiffened plates experimentally and checked the minimum stiffness requirement of longitudinal stiffeners in plates for local buckling. The buckling of stiffened isotropic cylindrical panels using the finite element method has also been studied by Tran *et al.* (2014).

Moreover, the static buckling load of a stiffened cylindrical panel made of composite materials has been investigated using the finite element method by Bushnell and Bushnell (1996). The authors also presented an optimum design of a stiffened cylindrical panel. Abramovich *et al.* (2003) reported experimental results of blade stiffened laminated composite cylindrical panels subjected to axial load and studied the buckling and postbuckling behaviour of these panels. Zimmermann *et al.* (2006) reported the experimental results of the buckling analysis and post-buckling analysis of composite cylindrical panel with various curvatures, number of stiffeners, and skin thicknesses.

Furthermore, the buckling and post-buckling behaviour of stiffened composite cylindrical panels subjected to axial and torsional loads was studied experimentally and numerically by Abramovich *et al.* (2008). Prusty (2008) reported the results of free vibration analysis and buckling analysis of cylindrical panels with different stiffener geometries using the finite element method. Abramovich and Weller (2009) investigated the buckling and postbuckling of stiffened cylindrical panel experimentally and numerically and reported that the J-type stiffener used in stiffening the panels although have a higher collapse load but does not improve the local static buckling. Bisagni and Vescovini (2009) studied the local buckling and post-buckling response of isotropic and composite stiffened plates using an analytical method and compared the results with the finite element method. Abramovich and Weller (2010) investigated the buckling and post-buckling of composite stiffened cylindrical panels subjected to loads in the post-buckling range. The authors concluded that there was no degradation in the load-carrying capacity of the panel due to repeated application of buckling loads.

Recently, Ni *et al.* (2015) presented an exhaustive literature survey on the buckling of stiffened cylindrical panels and cylinders between the years 2000-2012. Sastry *et al.* (2015) investigated the buckling of laminated composite stiffened cylindrical panels using the finite element method and reported results of stiffener geometries and ply orientations. Patel and

Sheikh (2016) investigated the buckling of a stiffened composite plate subjected to partial edge loading using the finite element method and reported results of the effect of stiffener orientation, ply orientation, loading patch on static buckling of stiffened plates. Priyadharshani *et al.* (2017) studied the buckling and failure of stiffened composite plates with cutouts subjected to combined in-plane and transverse loads experimentally and using the finite element method.

Summary

It is observed that the static buckling of cylindrical panels made of isotropic and composite materials have been investigated using numerical, analytical and experimental methods thoroughly. Considerations have been given by many authors on the influence of various parameters such as boundary conditions, material properties, geometry, imperfection, loading conditions, presence of cutouts and presence of stiffeners on the buckling behaviour of cylindrical panels.

2.3 Parametric Instability

The articles on the parametric instability of plates and cylindrical panels made from isotropic and composite materials are reviewed in this section. First, the parametric instability of plates, plates with cutouts and stiffened plates are considered and next, the parametric instability of cylindrical panels, panels with cutouts and stiffened panels are presented.

2.3.1 Plates

In this section, the studies related to the Parametric instability analysis of isotropic plates, composite plates, isotropic plates with cutouts, composite plates with cutouts, isotropic stiffened plates and isotropic composite plates by various authors are presented. The investigations concerning analytical methods, numerical methods and experimental methods are considered.

The parametric instability analysis of isotropic plates has been studied by many researchers. Hutt (1968) determined the parametric instability regions of isotropic plates using the finite element method. Simons and Leissa (1971) examined the parametric instability of isotropic plates subjected to acceleration loads. Simitse (1987) reported a review of literature on

parametric instability of plates and stated that parametric instability is a common phenomenon in the case of fluid-solid interaction problems. Aboudi *et al.* (1990) investigated the parametric instability of isotropic plates using a method where the Lyapunov exponents are evaluated. Ostiguy *et al.* (1993) performed experiments for investigating the parametric instability of isotropic plates. The authors also gave an analytical solution for parametric instability of isotropic plates.

Apart from these, the parametric instability of isotropic plates produced with viscoelastic material was investigated using Lyapunov exponents by Touati and Cederbaum (1994). Deolasi and Datta (1995) presented a finite element formulation considering the transverse shear deformation for studying the parametric instability of isotropic plates subjected to compressive and tensile loads. Deolasi and Datta (1997) reported the results of an experimental study on parametric instability of isotropic plates subjected to tensile loads. Ganapathi *et al.* (2000) discussed a plate element in the framework of the finite element method to analyze the non-linear parametric instability of isotropic plates. Chattopadhyay and Radu (2000) studied the parametric instability of isotropic plates using the finite element method based on higher order theory and compared the results with other plate theories. Sahu and Datta (2007) reported an exhaustive review on the study of parametric instability of isotropic plates and composite plates between the years of 1987 and 2005.

Besides, the parametric instability of composite plates has also been investigated by many authors. The parametric instability of unsymmetrically laminated composite plates was investigated analytically by Birman (1985). Srinivasan and Chellapandi (1986) studied the parametric instability of laminated plates with clamped boundary conditions using the finite strip method. Bert and Birman (1987) examined the influence of shear deformation on parametric stability of antisymmetric angle-ply plates neglecting in-plane and rotary inertia. Librescu and Thangjitham (1990) examined the parametric instability of shear deformable composite plates using a higher order nonlinear theory for symmetrically laminated plates. Using the finite element method, Moorthy *et al.* (1990) investigated the parametric instability of cross-ply and angle ply composite plates with various boundary conditions. Chen and Yang (1990) using the finite element method reported the results of parametric instability analysis of

angle ply composite plates. Cheng-Ti (1991) reported the results of parametric instability of composite plates with initial imperfection using numerical method.

Furthermore, using finite element formulation based on higher order theory, the results of parametric instability of composite plates with simply supported and clamped boundary conditions have been reported by Kwon (1991). Mond and Cederbaum (1992) analyzed the parametric instability of angle-ply and cross-ply laminated plates using the method of multiple scales and observed that besides the principal instability regions, some other cases could be of importance as well. Ganapathi *et al.* (1999) proposed an eight noded plate element for investigating the non-linear parametric instability of composite plates. Patel *et al.* (1999) investigated the parametric instability of composite plates supported on an elastic foundation using the finite element method and reported the effect of elastic foundation stiffness on parametric instability of the composite plate. Wang and Dawe (2002) investigated the parametric instability of composite plates using the finite strip method and reported the effects of ply orientation and boundary conditions on instability regions. Radu and Chattopadhyay (2002) presented the results of parametric instability analysis of delaminated composite plate using the finite element method. Singha and Daripa (2009) analyzed the parametric instability of isotropic and composite plates with various boundary conditions using the finite element method.

Recently, Ramachandra and Panda (2012) investigated the parametric instability of composite plate subjected to non-uniform in-plane loads employing the finite element method. Sahoo and Singh (2015a) investigated the effects of boundary conditions on the parametric instability of composite plates using the finite element method based on zig-zag theory. Mohanty *et al.* (2015) investigated the effect of delamination area on the parametric instability of delaminated cross-ply laminates using the finite element method. Sahoo and Singh (2015b) studied the parametric instability of composite plates subjected to static and periodic loads using the finite element method based on inverse hyperbolic zigzag theory. Yusof and Rasid (2016) reported the results of parametric instability analysis on an angle-ply composite plate using the finite element method. Loja *et al.* (2017) presented the results of the study on parametric instability of composite plates with variable stiffness using the Rayleigh-Ritz method. Darabi and Ganesan (2018) studied the parametric instability of cross-ply laminated

plates using a numerical method based on the non-linear analysis. Adhikari and Singh (2020) studied the parametric instability of composite plate subjected to various non-uniform in-plane loads using the finite element method.

The parametric instability of isotropic plates with cutouts has been dealt with by a few authors. Carlson (1974) studied experimentally the parametric instability of isotropic plate with a small cutout at the centre of the plate. Datta (1978) performed experiments to study the parametric instability of an isotropic plate with a central cutout at the centre in the shape of a rectangle but with elliptical ends. The parametric instability of isotropic plates with concentrated periodic tensile loading at various locations on the edges through experiments has been studied by Deolasi and Datta (1997). Prabhakara and Datta (1997) investigated the influence of cutout on the parametric instability of isotropic plates subjected to compressive and tensile periodic loads using the finite element method. Awrejcewicz *et al.* (2009) with the help of R-functions method, studied the parametric instability of isotropic plate with square cutout. Recently, Awrejcewicz *et al.* (2016) presented a numerical method for investigating the parametric instability of composite plates with central cutout based on R-functions and variational method.

Besides, stiffened plates composed of isotropic material has been also been considered. Thomas and Abbas (1983) presented the results of parametric instability analysis of stiffened isotropic plates using the finite element method. Mukhopadhyay (1989a, 1989b) reported that the results of vibration of stiffened plates obtained by consideration of the axial displacements differ only slightly when the displacements are ignored. Zeng and Bert (2001) demonstrated the application of differential quadrature method for the vibration analysis of eccentrically stiffened plates. The static buckling, vibration and dynamic instability of stiffened plate with and without cutouts subjected to uniform and non-uniform edge loads have been studied using the finite element method by Srivastava *et al.* 2003b, 2003c, 2003d, 2004 and 2005. Duffield and Willems (1972) investigated the parametric instability of stiffened plate subjected to sinusoidal dynamic forces by using an analytical approach. The authors also performed experiments to validate the analytical solution. Ma *et al.* (2012) used the method of multiple scales to calculate the results of vibration of a stiffened plate with four edges clamped.

Furthermore, for composite stiffened plates subjected to partial edge loading and concentrated edge loading was considered by Patel *et al.* (2009) using the finite element method. Attaf and Hollaway (1990) reported the analytical results of the vibrational analysis of stiffened composite plates. The authors also used an experimental technique to verify the analytical method. Liao and Cheng (1994) studied the parametric instability of stiffened plates and cylindrical panels using the finite element method and reported the results of the effect of lamination scheme and stiffening scheme of the parametric instability of stiffened plates.

Summary

It is observed that the Parametric instability of plates made of isotropic and composite materials has been investigated thoroughly. The effect of various parameters like geometry, material, delamination, boundary conditions cutouts and stiffeners have also been considered by the authors. Analytical, Experimental and Numerical methods have been considered for understanding the static buckling behaviour of plates.

2.3.2 Cylindrical panel

The articles related to parametric instability analysis of cylindrical panels are reviewed in this section. Cylindrical panels made of isotropic and composite materials are considered.

The parametric instability analysis of isotropic cylindrical panels has been performed by some authors. The vibration of a cylindrical panel on an elastic foundation has been investigated by Ramachandran and Murthy (1976) and Massalas and Kafousias (1979) using a numerical method. Sinharay and Banerjee (1985) reported the results of vibration of cylindrical panels with movable and immovable edges. Foale *et al.* (1998) investigated the applicability of dimension reduction methods for numerical methods to be used in the vibration analysis of cylindrical panels. Ng *et al.* (1999) using Bolotin's method reported the results of parametric excitation of isotropic cylindrical panels and compared the results obtained from CPT and FSDT. The three-dimensional Ritz method has also been considered to study the vibrational analysis of cylindrical panels (Liew *et al.*,2000). Moussaoui and Benamar (2002) presented a very comprehensive literature review on the vibrations of shells of various geometries.

Moreover, experiments were performed to study the harmonic excitation of cylindrical panels by Amabili *et al.* (2003). Popov (2003) presented the results of an analytical study on the linear and non-linear parametric instability analysis of cylindrical panels. The authors reported that the linear theory provides inaccurate results for certain vibration amplitudes. Amabili (2005) studied the vibration of simply supported cylindrical panels subjected to harmonic excitation using numerical methods. Amabili (2006) presented the results of experimental and numerical studies on the harmonic excitation of cylindrical shells. Amabili (2007) investigated the influence of boundary conditions of the vibration of cylindrical panels using numerical methods. The author also calculated the Lyapunov exponents and the Lyapunov dimension to check the presence of hyperchaos. Alijani and Amabili (2014) reported an exhaustive literature review of the articles related to vibrations of shells of various geometries and materials.

The parametric instability analysis for composite panels has been performed by a few authors. Sinha and Rath (1975) studied the vibration of a composite cylindrical panel using an analytical method and reported the influence of shear deformation and curvature of the panel on the vibration of panels. Loy *et al.* (1999) reported the results of the effect of boundary conditions and ply orientation on the vibration of cylindrical composite panels using a generalized differential quadrature method. Zhao *et al.* (2003) reported the mathematical formulation for a meshfree approach for vibration analysis of composite cylindrical panels. Patel *et al.* (2014) presented a model in the finite element framework for the vibrational analysis of composite cylindrical panels. Samukham *et al.* (2019) studied the parametric instability of cylindrical panel with variable angle tow laminates using the finite element method.

Additionally, cutouts in cylindrical isotropic and composite panels have considered by very few authors. Sahu and Datta (2002) reported the results of parametric instability of isotropic shell panels including a cylindrical panel with square cutout using the finite element method. Sahu and Datta (2003) studied the parametric instability of composite shell panels including a cylindrical panel with square cutout using the finite element method. Kumar *et al.* (2005) investigated the parametric instability of composite shell panels including a cylindrical panel with a circular cutout at the centre using the finite element method. Fazilati and Ovesy (2012)

using the finite strip method studied the parametric instability of cylindrical panels with a rectangular cutout.

Furthermore, the parametric instability analysis of stiffened cylindrical panels has been conducted by very few authors. Liao and Cheng (1994) investigated the influence of lamination scheme and stiffening scheme on the parametric instability of stiffened cylindrical panels. Sivasubramonian (1999) calculated the natural frequency of a stiffened cylindrical panel with a square cutout at the centre using the finite element method. Also, the static buckling behaviour of composite cylindrical panels with cutouts is considered. The instability analysis of stiffened cylindrical panels amongst other shell geometries with and without cutouts subjected to uniform and partial edge loads have been presented by Patel *et al.* 2006, 2007, 2009 and 2010. Fazilati and Ovesy (2013) using the finite strip method reported the results of parametric instability of stiffened panels with square cutout.

Summary

It is observed that the parametric instability of cylindrical panels made of isotropic and composite materials have been examined using numerical, analytical and experimental methods. Considerations have been given by many authors on the influence of several parameters such as boundary conditions, material properties, geometry, loading conditions, presence of cutouts and presence of stiffeners to investigate the parametric instability of cylindrical panels.

2.4 Stability due to Suddenly Applied In-Plane Pulse Loads

In this section, the articles on dynamic buckling of plates and cylindrical panels are presented. The idea of dynamic buckling of structures was first considered for columns and cylinders, where the effect of a short duration of load on the stability of structures was checked. These short-duration loads were perceived as impact loads acting for a certain duration. The earliest articles on the dynamic buckling phenomenon (Taub,1934; Koning and Taub,1934) considered isotropic columns subjected to pulse load for a finite duration without consideration of axial inertia. The dynamic buckling of shells was considered by Hutchinson and Budiansky (1966), Budiansky and Hutchinson (1966) and Budiansky (1967). The authors articulated criteria for

determining the dynamic buckling load of imperfection sensitive structures which are being used even today.

Furthermore, the dynamic buckling of isotropic plates has been studied by some authors. Weller *et al.* (1989) evaluated the dynamic load amplification factor (DLF) of plates using an analytical method and reported the influence of imperfection and loading duration on the DLF. The dynamic buckling of plates subjected to fluid-solid slamming was investigated experimentally by Cui *et al.* (1999). The experimental results were compared with the finite element results (Cui *et al.*, 2001) and the authors defined the dynamic buckling load as the load at which the transverse load increases rapidly. Petry and Fahlbusch (2000) presented a criterion for calculating the dynamic buckling of isotropic plates based on the stress in the plate. Kubiak (2007) proposed a criterion for calculating the dynamic buckling load of thin plates. Kowal-Michalska (2010) investigated the dynamic buckling of plates subjected to sinusoidal and rectangular pulse loads using the finite element method and reported that Volmir's criterion in many cases gives the results very close to the results obtained from Budiansky-Hutchinson criterion. Azarboni *et al.* (2015) presented the results of the dynamic buckling analysis of isotropic plates with various boundary conditions and subjected to dynamic and quasi-static loads. The authors also reported the results of pulse loads in the form of rectangular, sinusoidal, exponential and damping using numerical methods. The dynamic buckling of isotropic plates with elastically restrained edges was investigated by Yang and Wang (2017) using a numerical method.

Moreover, the dynamic buckling of composite plates has also been studied. Ekstrom (1973) investigated the dynamic buckling of orthotropic plates and reported that the load-deflection plot was oscillatory during the post-buckling stage, due to which, the stresses in the plate increase in the dynamic loading case when compared with the static loading case. Gilat and Aboudi (1995) studied the dynamic buckling of composite plates subjected to impulse loads using a numerical method in conjunction with micromechanical analysis. Abramovich and Grunwald (1995) presented the experimental study on the dynamic buckling of composite plates and reported that the presence of geometric imperfections decreases the dynamic buckling resistance of the plates. Papazoglou and Tsouvalis (1995) presented an analytical method for the dynamic buckling behaviour of composite plates with imperfections and

damping. Ari-Gur and Simonetta (1997) presented the results of dynamic buckling analysis of composite plates and reported that for a certain range of loading frequencies near the fundamental frequency of the plate, the dynamic buckling occurs at lower loads.

Furthermore, Gilat and Aboudi (2002) demonstrated the use of Lyapunov exponents as the means of calculating the dynamic buckling of composite plates and reported that the results obtained by the method proposed by the authors were comparable to the results obtained from other dynamic buckling criteria. Kubiak (2005) studied the dynamic buckling of composite plates with different material properties in the width direction for increasing the stiffness of the plate in compression using an analytical-numerical method and the finite element method. The author utilized the Budiansky-Hutchinson criterion to determine the critical value of the dynamic load. Kowal-Michalska and Mania (2008) investigated the influence of the shape of pulse loading, duration of loading, imperfection on the dynamic buckling of isotropic and orthotropic plates using the finite element method. Czechowski (2008) studied the dynamic buckling of orthotropic plates using numerical method considering the flow theory of plasticity. The dynamic buckling analysis of thin plates has been presented in Kubiak (2013) where several results of an analytical-numerical method and the finite element method are presented. Recently, Mondal and Ramachandra (2020) investigated the dynamic buckling of composite plates with delamination using the finite element method. The authors considered the stress-based method as the dynamic buckling criterion.

Apart from these, the dynamic buckling of stiffened plates with imperfections subjected to pulse loads of various shapes using the finite element method has been investigated by Mouhat and Abdellatif (2015). The authors calculated the dynamic buckling load using Budiansky-Roth criterion. Yang and Wang (2016) presented a dynamic buckling criterion for calculating the dynamic buckling load of a stiffened plate having elastically restrained edges using a numerical method. the proposed criterion is based on the Budiansky-Hutchinson criterion. Mouhat *et al.* (2016) investigated the effect of pulse shape on the dynamic buckling of stiffened plates using the finite element method and reported that the stiffened plate when subjected to rectangular pulse load, the dynamic buckling load 40% lower than the static buckling load. Tao *et al.* (2004a) reported the results of the dynamic buckling analysis of stiffened plate subjected to fluid-solid impact load using a numerical method. The authors considered the Budiansky-

Roth criterion for dynamic buckling analysis and reported that for large imperfections in the stiffened plate, Budiansky-Roth criterion was not suitable (Tao *et al.*, 2004b). Featherston *et al.* (2010) investigated the applicability of digital image correlation for the dynamic buckling of stiffened plates subjected to in-plane impact loads. Wang *et al.* studied the dynamic buckling of stiffened plates subjected to impact load using both experimental and numerical methods.

Additionally, the dynamic buckling of cylindrical shells subjected to axial loads for a short duration can be found in many articles. The articles related to structures being suddenly applied with loads have been reviewed by Simites (1987). The studies related to dynamic buckling of rods, circular and square cylinders have been reviewed in the article by Karagiozova and Alves (2008). The dynamic buckling of isotropic bars, cylinders and plates is presented in Lindberg and Florence (2012). The authors presented the theory and the experimental results of structures subjected to axial impulse loads. A few other articles in the area of dynamic buckling of cylindrical shells (complete cylinders) include Lindberg and Herbert (1966), Lakshmikantham and Tsui (1974), Pegg (1991), Pegg (1992), Shaw *et al.* (1993), Schokker *et al.* (1996), Huyan and Simites (1997), Michel *et al.* (2000), Bisagni (2005), Rahman *et al.* (2011), Patel *et al.* (2011), Priyadarsini *et al.* (2012), Sun *et al.* (2013), Bisagni (2015) and Zaczynska *et al.* (2020).

However, only a few articles are available on the dynamic buckling behaviour of cylindrical panels. The stability of plates and shells of various geometries subjected to dynamic loads was considered by Vol'mir (1974). The author presented results of the effect of duration of loading for simply supported structures on the dynamic buckling behaviour. The criterion proposed by Vol'mir (1974) is still being used today. Chien and Palazotto (1992) investigated the dynamic buckling of cylindrical panel subjected to concentrated pulse load at the centre of the panel and defined the dynamic buckling load as the load at which unbounded displacement originates. Gao and Fatt (2012) investigated the dynamic buckling of composite cylindrical panels subjected to blast loads in the transverse direction using the finite element method. the authors considered the Budiansky and Roth criterion for calculating the buckling pressures. Less and Abramovich (2012) studied the dynamic buckling of composite stiffened cylindrical panel subjected to sinusoidal pulse load using the finite element method. The authors considered

Hutchinson-Budiansky criterion for dynamic buckling analysis and reported that the loading duration is critical in dynamic buckling of stiffened cylindrical panels.

Summary

It is observed that the dynamic buckling of plates made of isotropic and composite materials have been studied well. The influence of parameters such as boundary conditions, material properties, geometry, duration of loading, presence of cutouts and presence of stiffeners on the dynamic buckling behaviour of plates have been considered. The dynamic buckling behaviour of cylindrical panels has been investigated by a few authors with the help of Budiansky-Roth criterion and Hutchinson-Budiansky criterion.

2.5 Failure Studies

In this section, the studies related to the failure of composite plates and cylindrical panels are presented. Many investigations are available on the progressive failure analysis of composite structures. However, investigations where the first ply failure load of composite plates and cylindrical panels are calculated have been considered in this section.

Reddy and Pandey (1987) calculated the first ply failure load for plates with various lamination schemes using the finite element method. The authors considered maximum stress criterion, maximum strain criterion, Hoffmann criterion, Tsai-Hill criterion and Tsai Wu criterion. Bruno *et al.* (1993) investigated the reliance of ply failure on the plate dimensions, ply orientation and number of layers in plates using different failure criteria in the finite element framework. Kam and Sher (1995) presented a procedure for calculating the failure load of composite plates using non-linear theory and reported that the proposed theory was valid for a certain thickness of the plate. Chang (2000) experimentally studied the first ply failure of pressure vessel subjected to internal pressure using acoustic emission test. Prusty *et al.* (2001) calculated the first ply failure load for stiffened plates and spherical shells subjected to transverse loads with various ply-orientations using the finite element method. Prusty *et al.* (2001) calculated the first ply failure load of composite shells subjected to transverse loads using the finite element method and compared the results with various failure theories. Davila *et al.* (2003) presented a failure criterion for unidirectional ply orientation based on Hashin failure criterion and Puck failure criterion.

Literature review

Moreover, a worldwide failure exercise was conducted from 1998-2004, where, the contributors were provided with data set (material properties, specimen geometry and test conditions) and were asked to predict the failure of composite laminates based on their respective failure theories (Hinton *et al.*, 2004). This exercise led to a collection of various failure theories (19 nos.) for calculating the failure of composite laminates. Rattanawangcharoen (2005) presented the results of first ply failure analysis using the finite element method for a plate with various ply orientations and considering various failure theories. Daniel (2007) presented the procedures for determining the failure in composite structures for criteria presented in Hinton *et al.* (2004). Ray and Majumder (2014) calculated the first ply failure loads for a plate with various lamination schemes and subjected to triangular pulse load using the finite element method. the authors considered Maximum stress criterion, Hoffman criterion and Tsai-Wu criterion. Shahabi and Forouzan (2017) presented a failure criterion based on the energy release rate for composite structures and compared the results with the experimental data. Lou *et al.* (2017) reported a failure criterion based on micromechanics of composite structures using the finite element method.

Apart from these, Adali and Cagdas (2011) presented the best lamination scheme for a cylindrical panel under compression using optimization technique by considering the static buckling and the stress failure criterion. Sengupta *et al.* (2015) calculated the first ply failure load of a cylindrical panel roof structure using the finite element method.

Summary

It is seen that the first ply failure of composite plates subjected to transverse loads has been calculated analytically, numerically and experimentally. The first ply failure analysis for plates and cylindrical panels due to in-plane pulse loads is not found. Very few studies are available for the calculation of the first ply failure load of cylindrical panels.

2.6 Need for Further Research

Based on the literature survey carried out in the preceding sections, a few unexplored areas are identified to be explored in the current investigation.

- The dynamic buckling behaviour of laminated composite plates has been investigated by many authors. However, investigations incorporating both failure and dynamic buckling of plates are required to be conducted.
- The investigation on the stability and failure of cylindrical panels subjected to in-plane pulse loads needs to be carried out incorporating the influence of its geometry, pulse loading function and ply orientation.
- The influence of cutout on the stability and failure of cylindrical panels when subjected to in-plane pulse loads has to be investigated.
- The influence of stiffener on the stability and failure of laminated composite cylindrical panels when subjected to in-plane pulse loads has to be investigated.

2.7 Objectives of the Present Study

To investigate the unexplored areas in the research, the following objectives were identified.

- To study the non-linear dynamic buckling behaviour of laminated composite plates integrated with the first ply failure of composite plates subjected to in-plane pulse loads.
- To study the stability and failure of laminated composite cylindrical panel subject to in-plane pulse loads.
- Assess the influence of cutouts on the stability and failure of the laminated composite cylindrical panel subjected to in-plane pulse loads.
- To study the stability and failure of laminated composite stiffened cylindrical panel subjected to in-plane pulse loads.

Each objective is considered separately in this thesis. In the succeeding chapter, the details of the modelling are presented.



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