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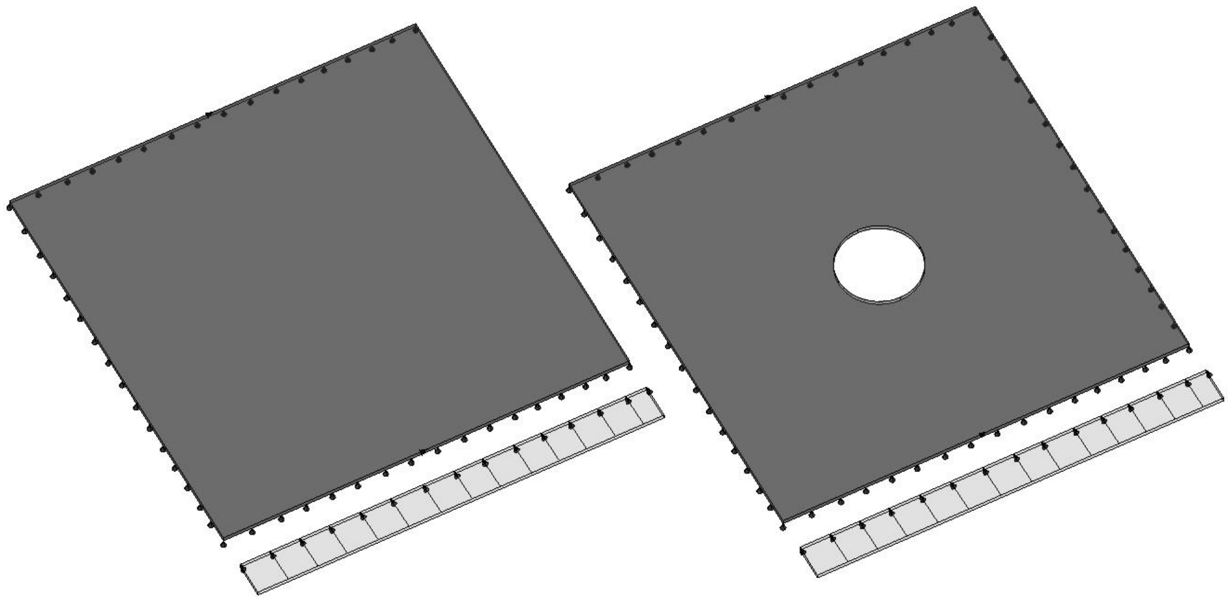

Buckling of thin-walled FRP plates under compression

A study on effects of boundary conditions and holes in the plate.

Master’s thesis in Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Master’s Thesis ACEX30-YY-NN
Gothenburg, Sweden 2020

MASTER'S THESIS ACEX30

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Cover:
Figure represents 3D models of FRP plates used in the analysis, Refer "Chapter 4&5" for more information.
Department of Architecture and Civil Engineering
Göteborg, Sweden, 2020

Behavior of thin-walled FRP under in-plane compression
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ABSTRACT

Advancement in technologies opens new ways to retrofit conventionally used material in the world. Due to recent rise in importance of sustainability and environmental preservation construction industry is obliged to switch to materials like Fibre reinforced polymers (FRP). Fibre reinforced polymer is a composite material made up of continuous fibres packed together with a resin. These fibres and resins can be made from different materials. For example, fibres are made of Glass or Carbon and resins can be epoxy or polymer based. FRP is used when high stiffness, high tensile strength and light weight design aspects are basic requirements in a structural component. Preliminary design codes need to be specified for FRP to standardize the material in this globalization era. Euro codes has many grey areas in stability of FRP composites under buckling.

Aim of this master's thesis is to develop buckling behaviour of FRP plates when subjected to uniform in-plane compression with specific boundary conditions, similar analysis is carried out with a hole in the middle of the plate in finite element solver "ABAQUS", only glass fibre polymers are used in this analysis. To standardize the new stability findings, a similar analysis to steel is made i.e., to extract a relation between buckling reduction factor and slenderness. Different matrices are created with different layups, thicknesses, and initial imperfections to extend the range of the study to match the real-world implications.

Key words: FRP, composites, buckling curves, FEM, ABAQUS.

Beteende hos tunnväggig FRP under kompression i plan

Examensarbete inom Structural Engineering and Building Technology

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SAMMANFATTNING

Framsteg inom teknik öppnar nya sätt att eftermontera konventionellt använt material i världen. På grund av nyligen ökad betydelse av hållbarhet och miljöskydd är byggindustrin skyldig att byta till material som fiberförstärkta polymerer (FRP). Fiberförstärkt polymer är ett kompositmaterial som består av kontinuerliga fibrer packade tillsammans med ett harts. Dessa fibrer och hartser kan tillverkas av olika material. Till exempel är fibrer tillverkade av glas eller kol och hartser kan vara baserade på epoxi eller polymer. FRP används när hög styvhet, hög draghållfasthet och konstruktionsaspekter är grundläggande krav i en konstruktionskomponent. Preliminära designkoder måste specificeras för att FRP ska standardisera materialet i denna globaliseringsperiod. Eurokoder har många grå områden i stabilitet hos FRP-kompositer under knäckning.

Syftet med denna masteruppsats är att utveckla bockningsbeteende hos FRP-plattor när de utsätts för enhetlig komprimering i plan med specifika gränsvillkor, liknande analys utförs med ett hål i mitten av plattan, endast glasfiberpolymerer används i denna analys . För att standardisera de nya stabilitetsfynden görs en liknande analys som stål, dvs för att extrahera en relation mellan knäckningsreduktionsfaktor och slankhet. Olika matriser skapas med olika layouter, tjocklekar och initiala brister för att utvidga studiens intervall så att de motsvarar verkliga konsekvenser.

Nyckelord: FRP, kompositer, knäppningskurvor, FEM, ABAQUS.

Contents

Preface

The thesis was performed from January to June 2020 at the Division of Structural Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden. The thesis is part of ongoing project at Chalmers University of Technology in the view of contribution to the technical specification document for future Eurocode.

The entire work on the thesis is attributed to the team of the project. First of all, we would like to thank our Examiner and Supervisor Reza Haghani, who is an expert in the field of Light weight structures who motivated us to take the project in fibre reinforced polymers. His knowledge and support during the course of thesis is invaluable. Secondly, we would like to thank our other supervisor Morteza Eskandari Ghadi (Tehran university), who helped us in keeping afloat with the necessary theoretical knowledge to carry out the thesis. Our gratitude goes to both these individuals who motivated and supported us through the tough times of COVID-19 pandemic which is considered as the darkest times of 21st century.

We also like to thank all the experts who made substantial research in the field which enabled us to develop pre-requisite knowledge to carryout thesis.

Finally, we would like to show the gratitude towards each other for the collaboration in the team during thesis work. Likith and Suraj appreciates each other's knowledge and inputs into the work. It was challenging to work remotely due to the restrictions caused in social life due to the pandemic. Yet both them have managed to bring out the best possible output in the thesis. Likith and Suraj believe that all the difficulties and challenges experience during the thesis will be rewarding in the future.

Gothenburg, June 2020
Likith Kunal Gorantla and Surajkumar Bangalore Srinivasa

Notations

Roman upper-case letters

A	cross-section area
E	modulus of elasticity
I	moment of inertia
N_{cr}	critical buckling load
P	uniform compressive load
R_{crit}	critical buckling load (first order buckling, FEA)
R_{fail}	failure load (second order buckling, FEA)
R_{ult}	ultimate compressive load (first order compression, FEA)
S_{12}	in-plane strength

Roman lower-case letters

b	width
d	diameter
t	thickness

Greek lower-case letters

$\bar{\lambda}$	relative slenderness
χ	buckling reduction factor
λ	slenderness
ϑ	Poisson's ratio
ρ	density
σ_{crit}	critical buckling stress (first order buckling, FEA)
σ_{fail}	failure stress (second order buckling, FEA)
σ_{max}	maximum resistible stress
σ_{ult}	ultimate compressive stress (first order compression, FEA)

Abbreviations

CEN	European Committee for Standards
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
GFRP	Glass Fibre Reinforced Polymer
ULS	Ultimate Limit State
UV	Ultraviolet
UD	Uni-Directional
WWEF	World-Wide Failure Ex

1 Introduction

Fibre reinforced polymers (FRP) are composite materials build by binding fibres in specific orientation together with a resin. Strength of this material excessively depends on the mechanical properties of the fibres while the purpose of the resin is to hold the fibres together, distributed the stresses in the matrix and protection against any environmental damages. Main advantages of FRP are high strength to weight, stiffness to weight ratios, material is extremely light weight and exerts noncorrosive properties while cost being the only disadvantage. Industries with structural integrity and light weight design obligations prefer FRP over conventional material, Aeronautical, Automotive, marine and construction industries being the top industries to do so. As the cost of FRP reduces over time every other industry seeks to introduce the material due to the high-performance capabilities. As the conventionality of the material increases various aspects such as safety and reliability come in play thus leading to developments in design code in order to standardize material.

Purpose of the design codes is to validate the usage and safety of material before its application in any structure. Currently in Europe the standards are developed by "European Committee for Standardization" (CEN), standard which are specifically developed for construction industry is known as "Eurocode". Materials like concrete, timber, steel have standard codes put in place in Eurocode but section of codes for FRP composite material are not yet emerged. Various prospects are being currently developed to standardise composite materials one of them is "Prospect for New Guidance in the Design of FRP by Ascione et al (2016)". This need for the development of codes defines the purpose of this current thesis.

1.1 Aim & objective

The principal aim of this thesis is to study the buckling behaviour of thin walled FRP plates subjected to in-plane compression. The emphasize is on the study of buckling and post-buckling behaviour of the plates designed with variable boundary conditions and holes. The focus of the thesis is to carry out a substantial research on the state-of-art literature and existing experimental data on the buckling behaviour of thin walled FRP plates subjected to in-plane compression loading. Followed by a parametric study using Finite Element Method (FEM) to analyse thin walled FRP plates subjected to in-plane compression loading with variable boundary conditions, multiple layups, different imperfection factors, width-to-thickness ratios, and consideration of presence of a hole. The crux of the thesis lies in study of relationship between the buckling reduction factor and slenderness by developing the buckling curves from the analysis of FRP plates under the influence of previously mentioned parameters. From the comprehensive perspective, the aspiration for this thesis is contribution to the technical specification document for future Eurocode.

The objectives of the thesis are articulated as the following:

- ✓ To carry out state-of-art research on the concepts and methodologies used in the analysis for buckling behaviour of simply supported thin walled FRP plates subjected to in-plane compression.
- ✓ To acquire experience in using FEM to analyse FRP members in general, FRP plates in specific.
- ✓ To perform parametric analysis based on the aim mentioned in the thesis using ABAQUS software and Python scripting.
- ✓ To analyse the relationship between slenderness and buckling reduction factors based on the mentioned parameters.
- ✓ To develop data for the buckling curves and to validate the generated data with technical interpretations based on the fundamentals of plate buckling theory.
- ✓ To contribute for the scope of future study on the buckling behaviour of FRP plates by suggestions based on the experience.

1.2 Method

The state-of-art study on FRP plates subjected to in-plane compression was conducted based books, published journal articles and technical reports from various structural engineering composite researchers and institutes. The literature study resulted in developing an overall understanding of FRP composite and its properties, theoretical and parametrical studies on FRP plates. Specific knowledge on buckling and post buckling behaviour FRP plates subjected to in-plane compression paved a rightful path carry out parametric studies in accordance with the aim of the thesis. A pre-study was carried out to get familiarised with proposed standards in the future

Eurocode for FRP composites and to incorporate Finite Element Method for the analysis of FRP composites.

The parametric study on the post buckling behaviour of FRP plates subjected to in-plane compression was performed by designing two FRP composite plates made from Glass-epoxy material with four unique layups, six thicknesses, two different boundary conditions and one plate with a hole in the centre. The plates were analysed for its buckling behaviour. The commercial Finite Element software ABAQUS was used to model the plates. To manage the complexity and the volume of analysis, Python scripting was used. To obtain the required stresses to calculate buckling reduction factor and slenderness, three finite element analyses was carried out namely, first order buckling analysis, second order buckling analysis and first order compressive analysis for each plate configuration. The methodology for each step is described in detail in the following chapters.

1.3 Limitations

The limitation for this thesis is based on the requirements to achieve the outlined objective. The research on state-of art- is limited to information on behaviour of plates subjected to only in-plane compression loads. The parametric analysis was confined to square plates made of Glass Fibre Reinforced Polymer composites. The focus on the outcome of thesis is mainly for the structural applications in construction industry. In case of plate with the hole, the diameter of the hole is kept constant and the location of the hole is restricted to the centre of the plate. The tools used to perform the Finite Element Analysis was confined to ABAQUS.

2 Introduction to FRP Composites

The advancement in science has paved a way to develop several composite materials, which can be used as constitutive part with the conventional materials. In modern times, the composites are being used as the alternative for the conventional materials. The usage of these composite materials is important in the future to create a sustainable structure. The composite materials are characteristically developed to be light weight, without compromising on the strength of the material and the other properties such as stiffness, toughness etc, A typical composite material consists of two or more materials, of which a discontinuous phase (reinforcement) and a continuous phase (matrix) are embedded together. The material properties of each phase and interface between one another determines the distinction of the composite. Out of many such composite materials, Fibre Reinforced Polymers (FRP) is widely used in industries such as Aerospace, Automotive, Marine, Electrical and Construction (Zoghi, 2014). This chapter demonstrates the key constituents of FRP (reinforcement and matrix).

2.1 Reinforcement

Reinforcement in FRP composites are typically made of Fibres. The fibres in the reinforcement can be made in different configurations of materials, geometry, and orientation within the matrix. The composites are basically divided into two subgroups based on the type of reinforcement namely, Fibre reinforced composite and particle reinforced composite. The fibre reinforcement is typically long and its ability to perform at high temperatures, withstand fractures as cracks are developed normal to the fibre length, is meritorious. The particle reinforcement is an evenly dimensioned used as a supplement to the matrix in order to magnify the stiffness of the composite. The potential of fibre reinforcement is much higher than particle reinforcement in terms of carrying loads during impact (Zoghi, 2014).

The fibre reinforcement can be made of different materials such as glass, carbon, and organic fibres. Carbon fibres are used in high performing FRP composites as it possesses high strength and high modulus. But its inferior performance during the impact makes it vulnerable to damage. The other drawback is the cost of the material. Organic fibres popularly known as Arbid fibres are tough and provide very high impact resistance. But it fails to demonstrate resistance against compression and bending (Zoghi, 2014). The description regarding glass fibres is mentioned in the next section as it is the chosen material in this thesis.

2.1.1 Glass fibres

The glass fibres are extensively used in structural applications as it is cheap compared to carbon and organic fibres. The advantage is it possess high strength and conventional glass properties such as hardness, resistance to corrosion etc. The applications of Glass Fibre Reinforced Polymer's (GFRP's) are pronounced in industries such as Aerospace, Construction, Automotive, Electrical, Marine etc.

The main constituent of glass fibre is silica (SiO_2). The silica along with other materials such as limestone, alumina and an ionic catalyst are heated to about $1260°C$ to manufacture the glass fibre reinforcement (Agarwal et., 2018). The manufacturing of glass is dependent on the composition of ingredients to produce fibres with variable material properties (Ascione et., 2017). Two types of glass fibres are widely used in structural applications, namely Electrical glass (E-glass) and Strength glass (S-glass). The S-glass is characterised with high strength and stiffness. The E-glass is also characterised with high strength and durability, and its low cost makes it favourable glass fibre variant across the industries (Uddin, 2013).

2.1.2 Forms of fibre reinforcement

The load bearing capacity of the FRP composites is majorly dependant on its reinforcements. The forms of fibres chosen in the reinforcements are important. Basically, fibre reinforcements are categorised into continuous and discontinuous fibre reinforcements.

2.2 Matrix

Matrix plays a pivotal role in creating the bonds between the fibres. The distribution of loads between the fibres and the protection of fibres from physical damages, chemical damages etc are monitored by matrix. The matrix in FRP are made of resins, additives, and fillers. The mechanical properties of the FRP composites such as compressive, shear and transverse strength are monitored by matrix (Zoghi, 2014).

The resins FRP can be made using materials such as metals, polymers, or ceramics. The usage of resins made by polymers over the metals, is evident in the construction industry owing to the former's cost effectiveness. A brief description regarding polymer resins is presented in the next section

2.2.1 Polymer resins

As mentioned earlier, the polymer resins are widely used due to its attributes such as low-density, chemical, and electrical resistivity, cost effectiveness and ease of fabrication. Nevertheless, certain properties such as moisture absorption, UV-radiation sensitivity, response to higher temperatures, low stiffness are demeritorious. The polymers are produced by a process called as polymerization, which is made by establishing a backbone of carbon-atoms associated with a chain of other atoms or several groups of atoms. The molecules created by these atoms determines the behaviour of the polymers against heat. Based on its response to the heat, the polymers are classified into thermosetting polymers and thermoplastic polymers (Agrawal et al., 2018).

Thermoplastic polymers are made of molecules created by weak Van der Waals bonds. Thermosetting polymers are made of molecules created by covalent bonds (Agrawal et al., 2018). Thermoplastic polymers tend to melt when exposed to high temperatures, thus making it undesirable. On the other hand, thermosetting polymers are preferred in construction industry due to its superior mechanical and chemical properties, and durability.

Thermosetting polymers generally used in construction industry are epoxy, polyester, and phenolic resins (Zoghi, 2014). The epoxy and polyester resins along with vinyl ester, are the chosen types for fabrication of fibre reinforcement with high performance requirements (Agrawal et al., 2018).

2.2.2 Fillers and additives

The usage of fillers and additives in the matrix are common as they provide additional aids to the matrix in terms of stiffness, reduction of shrinkage, viscosity control etc. In addition, the usage of fillers reduces the cost of production (Agrawal et al., 2018). The fillers are quite effective in terms of providing better fire resistance due to its ability prevent fibres from adhering to composite surface. The usage of fillers is disregarded in high performance FRP composites as the former effects the load carrying through fibres and resins and creates negative impact on toughness quotient of resins. Kaolin (China clay), silica, calcium carbonate, talc and glass microspheres are few of the regularly used fillers in FRP composites.

Additives are also used in FRP composites to enhance its performance. The addition of antimony oxide boosts fire resistance. Usage of magnesium oxide and Calcium hydroxide thickens the matrix (Agrawal et al., 2018).

3 Buckling behaviour of FRP plates

The objective of thesis is to investigate the behaviour of thin walled FRP plates subjected to in-plane compressive loading. The plates initially exhibit stability and will undergo simple compression until loading reaches critical. Post critical loading, the plates may buckle. Such behaviour of instability has been analysed in the past and several theories have been proposed. The buckling behaviour of FRP plates with different boundary conditions and plates with the presence of a hole has been illustrated in this chapter.

FRP composites are extremely efficient as a construction material when compared to the conventional materials. The design of FRP plates are characterised list with several aspects. The plates must be designed for the stability. The segment dealing with the stability is steady still a work in progress and the technical specifications for which is provided in the proposed Eurocode prospect. Since the FRP sections are made of flat panels, the designer needs to consider the effect of local and global buckling and its influence on the resistance of the cross section. These FRP profiles when designed as columns, the local buckling will we developed in the web or the flange. These parts maybe further have studied as plates. The proposed codes for FRP composites profiles indicates that the buckling theory is like that of the Steel profiles (Al-Emrani & Åkesson, 2012).

The current analysis focuses on the FRP plates with a hole and a plate with a 3-sided boundary conditions subjected to in-plane compression loading. The produced data through the analysis will be proposed for the development of the future Eurocode. The methodology and the results comprising data will be presented in the next chapters. The theory behind the method of analysis and results generation have been presented in this chapter.

3.1 Buckling theory of composite plates

When in-plane compressive loads are applied on the plates, initially plates showcase stability and in- plane displacement. As the application of loads progress towards higher magnitude the instability is developed in the plates, giving rise to out-of-plane displacements. The plate buckling is characterised with reference to this load versus of out-of-plane displacement (Turvey & Marshall, 1995). The loads at these significant displacements are termed as Critical loads. The buckling theory says that, at this point of critical loading the load versus out-of-plane displacement curve exhibits bifurcation behaviour. The response of the plate to pre and post this critical loading point is differed (Agrawal et al., 2018). The curve corresponding to the post bifurcation point indicates the post buckling behaviour of the plate. In this chapter, both pre-buckling and post-buckling behaviour of plates are illustrated.

3.1.1 Behaviour up to the critical buckling load

Thin plates in this phase behave in accordance with the classical buckling theory. And this theory is based on Kirchhoff's hypothesis. It states, "Normal to the mid-plane remain straight and normal as the plane deforms into a surface " (Turvey & Marshall, 1995). Based on this theory, critical buckling load can be derived. The critical buckling load can be availed by the aid of in-plane forces (N) and moment resultants (). Since the actual derivation is out of scope for this thesis, the procedures involve developing a constituent relationship. It involves relationship between in-plane force, moment resultants, mid-plane strains and plate curvatures (N, M, ε^0 and K respectively). The elastic coefficients of each ply of the plate (A, B and D) are used with the above relationship forms the symbolic equation 3.1 (Turvey & Marshall, 1995).

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ K \end{bmatrix} \tag{3.1}$$

If the plies are unsymmetrically oriented with respect to the mid plane, the coupling matrices (B- matrices) will be not be zero. These matrices indicate the presence of coupling between bending and stretching in the laminates. Further, with the aid of equilibrium forces and moments equation a differential equation for buckling can be derived. The differential equation for buckling comprises a coupling between in-plane loads and the out-of-plane displacements. By the application of boundary conditions, an eigen value problem of differential equations will be derived to calculate critical buckling load. Each of these non-dimensional eigen values corresponds to the buckling loads and the lowest of which will be the critical buckling load (Agarwal et al. 2008). Although eigen value problem does not produce accurate values of critical buckling loads. Numerical methods such as FEA and series methods as Fourier series can also be used and compared with the prevailing results.

3.1.2 Post buckling behaviour

The behaviour of the plate until the bifurcation point is linear, and in the previous section the process of calculating the critical buckling load have been established. But post this point of buckling, the plates still show the capacity to carry additional loading before it collapses or reaches the ultimate loading point. The corresponding behaviour of the plate is analysed as the post buckling behaviour of the plate. In several scenarios, the post buckling loads higher than the critical loads. However, the previous studies indicate that this additional load carrying capacity for composite plates are less than the steel plates. The theoretical post buckling analysis is a non-linear, as it accounts for large displacements (Turvey &Marshall, 19995). As mentioned earlier in the chapter, the focus is just on availing the procedure for post buckling analysis.

The non-linear behaviour is primarily attributed to the generation of extra in-plane strains produced from transverse displacements. The theoretical post buckling analysis neglects changes in geometric and material properties. In post-buckling phase, large out of plane displacements are generated and it will be examined by including stretching as additional terms in the in equation for mid-plane stress. This included extra terms are characteristically non-linear, which brings out changes in both constitutive relationship and differential equations. Finally, combining differential equations with the boundary conditions, an equilibrium is achieved to interpret the post buckling behaviour (Turvey &Marshall, 19995). FEA analysis can be used as numerical method to analyse and solve the post buckling behaviour. The initial FEA analysis was only based on Kirchhoff's hypothesis, at later stages researchers have developed FEA models by even including the shear deformations.

3.1.3 Failure of the composite

In composite plates, the failure will commence in either a single ply or several plies at a time when the loads are higher enough. And as the loading reaches ultimatum, all the plies will fail, and the entire plate will collapse. Many theories have been developed to analyse the failure, and the terminology is described as Failure criteria. The failure analysis is tedious and time-consuming process as it involves several iterative steps. The usage of commercial software's, such as Abaqus can perform complete analysis using FEA.

Theoretically, during composite failure analysis, the constitutive relation of the plate will be updated several times until the complete failure of structure. As we know, the constitutive relation can be used to obtain mid-plane strains and plate curvatures when in-plane forces and moments are available (Agarwal et.al, 2018). The stresses are obtained by using the constitutive relation. We can choose a criterion to examine the initial failure occurrence in a ply due to the applied loads. When the failure occurs in a ply, the constitutive relation will be affected so does the applied loads and the corresponding displacements. It is difficult to estimate elastic constants of each ply and the stiffness od failed ply will be assumed to zero. Thus, stiffness matrices in constitutive relation is altered appropriately. For each choice of in-plane forces and moments, the corresponding constitute relation can be generated to calculate increment in stresses. The stresses obtained from each step will be added to the preceding step and the summation of all the stresses are values against the failure criterion (Agarwal et.al, 2018).

There will be increments in forces and moments until the failure reaches another ply. And again, same procedure is repeated to update the stiffness matrix. The iteration continues until all the plies undergo failure. The stress at which the last ply is failed is called as failure stress and corresponding load is the failure load (Agarwal et.al, 2018).

The common failure criteria for the orthotropic plates is illustrated in the next section.

3.1.3.1 Common failure criteria

As mentioned earlier, failure criteria are used to predict the occurrence of failure. Several theories have been proposed for failure criteria. Earliest theory for failure criteria was proposed by Hashin and Puck in 1970's. It involves prediction of failure modes for the unidirectional lamina, compressive matrix failure and compressive fibre failure. The other notable theories are The Maximum Stress Theory, The Maximum Strain Theory and Maximum Work Theory (Agarwal et.al, 2018). But each of all these theories have its own limitations. According to The Maximum Stress theory failure initiates when stress components are larger corresponding yield strength in compression, tension, and shear. The interaction between different failure modes are neglected in this theory. The Maximum Strain theory claims that, failure initiates when strains in natural axis are larger than the respective permitted strain limits. The Maximum Work theory popularly known as Tsai-Hill criteria, considers interaction between stresses and strength criteria. Accordingly, the yielding for failure is reached when the failure index reaches unity. This theory considers interaction between different failure modes.

The proposed theories are evaluated in a Worldwide Failure Exercise (WWEF) which involves committee of expert researchers from the field. In recent years, a theory LaRC02 (2003) was proposed. The theory is derived from Hashin's and Puck theory, and it can predict matrix failures in both compression and tension and fibre failures in both compression and tension.

3.2 Design codes based on Eurocode standards

The ultimate aim of this thesis is to contribute for the development of Eurocode standards for the design and analysis of FRP plates. As the basis for study, it is important to understand the existing codes for materials which showcase similar buckling behaviour.

The design codes for all the structural members designed out of various building materials are based on Eurocode standards (European commission, 2018). In this thesis, the concentration is to understand the design of steel members for its stability. Based on the previous experiments and research, the analysis for steel plates involves developing a relationship between buckling reduction factor and slenderness. Based on this, further hand calculations for the design resistance of compression loads are performed (Al-Emrani & Åkesson, 2012).

For the development of future codes for FRP plates it is important to understand design codes of steel plates, as they behave like the latter especially in terms of buckling reduction factor to slenderness relationship. In the next section, the existing design codes for stability of steel members and steel plates are illustrated.

3.2.1 Design code for stability of steel members

According to Eurocodes, the buckling curves are used to determine the design resistance capacity of the structural members such as columns and plates. For a steel plate subjected to axial compressive loads, based on its characteristics such as shape and material properties, the design resistance can be obtained (Al-Emrani & Åkesson, 2012). The buckling curve is generated by developing a relationship between the buckling reduction factor (χ) and the slenderness (λ). Based on these curves, the resistant capacity of the member is reduced by multiplying the actual resistance capacity with the buckling reduction factor. The design process for obtaining the buckling curves for steel plates is described in the next section.

3.2.1.1 Buckling curves for steel plates

The buckling of plates subjected to in-plane compression loading, is an instability phenomenon which is solved by using Classical Euler theory (EN 1993-1-5). Based on the theory, a buckling curve constituting a relationship between buckling reduction factor and slenderness is derived. The plates may have supports or either three or more edges. The loading on the plates reaches the critical loading level, the stress distribution differs, and the stresses are induced in the direction of supports parallel to the loading plane. This creates a tension field in the plates in a transverse direction. This action aids plate to undertake extra additional loading, and it is referred as Post-buckling capacity (Al-Emrani & Åkesson, 2012).
Based on Classical Euler theory, the expression to calculate critical buckling stress (σ_{Crit}) is shown in equation 3.2. where 'E' is the modulus of elasticity, 'a' is the width of the loading plane, 'ϑ' is the Poisson's ratio. 't' is the thickness of the plate.

$$\sigma_{Crit} = \frac{\pi^2 * E}{12\,(1-\vartheta^2) * \left(\frac{a}{b}\right)^2} \tag{3.2}$$

However, for the plates having boundary conditions on 3 or more sides and subjected to in-plane compression loading, the expression 3.2 is modified based on Von Karman hypothesis. A buckling coefficient 'k' is introduced as the function of aspect ratio of the plate (a/b), number of buckles in longitudinal direction 'm' and the number of buckles in the longitudinal direction 'n'. The expression buckling coefficient is shown in equation 3.3.

$$k = \left[\frac{m * b}{a} + \frac{a}{m * b}\right]^2 \tag{3.3}$$

The modified expression for the critical buckling stress is shown in equation 3.4. The critical buckling stress will be lowest when number of buckles in longitudinal direction ‘n’. The width if the loading plane is modified into the effective width ‘’, which is the original width times the reduction factor.

$$\sigma_{Crit} = k * \frac{\pi^2 * E}{12\,(1-\vartheta^2) * \left(\frac{b_e}{t}\right)^2} \tag{3.4}$$

The slenderness,’ $\bar{\lambda}$’ and the buckling reduction factor, ‘χ’ are shown in expressions 3.5 and 3.6, respectively. The slenderness is calculated based on the relation between stress and slenderness with regards to the yield strength ‘f_y’. The buckling reduction factor will not exceed 1 as the maximum stress in the plate, ‘f_y’, can never be more than yield strength.

$$\bar{\lambda}= \sqrt{\frac{f_y}{\sigma_{Crit}}} \tag{3.5}$$

$$\chi = \frac{\sigma_{max}}{f_y} \leq 1 \tag{3.6}$$

The slenderness in the above equation is mainly dependent width-to-thickness ratio (b/t). The buckling reduction factor are varied upon initial imperfections and slenderness of the plate.

The buckling curves are generated based on the equations 3.2 and 3.4, which contemplate the relationship between buckling reduction factor and the relative slenderness of the plate subject to in- plane compression loading.

3.3 Proposed design code for stability for FRP plates

The European commission suggests a prospective design code for the calculations of Critical buckling loads both by hand calculations, experimental and numerical methods (Ascione et al.,2017). The simple problems can be solved by hand calculations, whereas for the plates with greater complexity requires numerical methods such as FEA. Software usage based on FEA is recommendable to perform both linear and non-linear analysis. The buckling shapes are obtained by linear analysis and in case of non-linear effect of initial imperfections must be included to obtain different buckling modes.

4 Buckling behavior of FRP composite plates with a 3-sided Boundary Condition

Analysis of FRP plate is carried out on "ABAQUS" Finite element solver with 3-sided boundary conditions. Methods & Results are presented below.

4.1 Methodology

Python scripts were written to define and create 72 FRP plate models, which were later used as an input for ABAQUS finite element solver. FRP composite plate models consisted of several unique layups with specific orientations and boundary conditions. Slenderness (λ) and Buckling reduction factor (χ) were the results of the analysis. In order to calculate these variables, Critical buckling stress (σ_{crit}), Failure stress (σ_{fail}), Ultimate compressive stress (σ_{ult}) and eigenvalues were needed. So, three different analysis are performed namely "First order buckling analysis", "Second order buckling analysis" and "First order compressive analysis". Slenderness & Buckling reduction factor are plotted against each other to create "Buckling Curves" for study of buckling behavior in plate with various inputs and conditions.

4.2 Description & Formulation

In First order buckling analysis FRP composite plate is considered to have an initial imperfection and without second order analysis. Plate is subjected to uniform compressive load "P" which is applied as a displacement boundary condition. Plate is restricted on 3 sides in Z direction, one side in X direction and at 2 point in Y direction placed for stability. Plate assumed to be made from a linearly variable elastic material. Eigen mode is set to "1" which looks like a half-sine curve. Buckling analysis is performed with above set variable to obtain eigenvalue, which is later used to calculate critical buckling stress, formulated as Equation 4.1. In Second order buckling analysis FRP composite plate is considered to have an initial imperfection. Plate is subjected to uniform compressive load "P" which is applied as a displacement boundary condition. Plate is restricted on 3 sides in Z direction, one side in X direction and at 2 point in Y direction placed for stability. Plate assumed to be made from a linearly variable elastic material with a failure criterion known as “Hashin Failure criteria” and damage evolution. Eigenmode from First order Buckling analysis is used here, Reaction forces (R_{fail}) are recorded on the side with X-direction restriction which is later used to calculate Failure buckling stress, formulated as Equation 4.2. In First order compressive analysis FRP composite plate is considered to have no initial imperfection. Plate is subjected to uniform compressive load “P” which is applied as a displacement boundary condition. Plate is restricted on 3 sides in Z direction, one side in X direction and at 2 point in Y direction placed for stability. Plate assumed to be made from a linearly variable elastic material with a failure criterion known as “Hashin Failure criteria” and damage evolution. Reaction forces (R_{ult}) are recorded on the side with X-direction restriction, which is later used to calculate the Ultimate compressive stress in the plate, formulated as Equation 4.3. Finally, Slenderness and Buckling reduction factors are calculated using following Equation 4.4 & Equation 4.5.

$$\sigma_{Crit} = \frac{Eigenvalue * P}{A} \tag{4.1}$$

$$\sigma_{fail} = \frac{R_{fail}}{A} \tag{4.2}$$

$$\sigma_{ult} = \frac{R_{ult}}{A} \tag{4.3}$$

$$\lambda = \sqrt{\frac{\sigma_{ult}}{\sigma_{crit}}} \tag{4.4}$$

$$\chi = \frac{\sigma_{fail}}{\sigma_{ult}} \tag{4.5}$$

4.3 Finite element Model

All the finite element models of FRP plates are simply supported on 3 edges with one free edge, Plates are also subjected to a uniform axial compressive load applied as a displacement boundary condition. All the FRP plates had constant length, width with altering variables mentioned below.

- 4 unique layups
- 6 thicknesses
- 3 imperfection factors

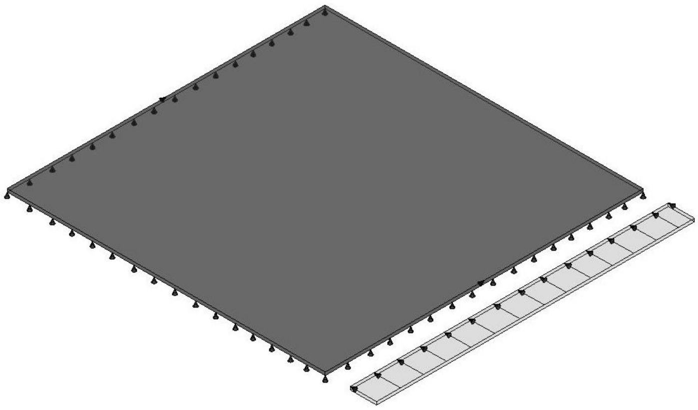

Figure 1: 3D model of Finite Element model with 3-sided boundary conditions

Python scripts were used as inputs for ABAQUS in order to rerun the program for 72 unique FRP composite plate models. Scripts also provided immense amount of flexibility in changing all the 72 models at once to adapt for varying decisions along the timeline of the thesis. They also provide the confidence in error free input and output.

Another major variable in the thesis is finite element software ABAQUS itself. Following "Figure 2" shows a brief overlook of the process of analysis in ABAQUS followed by a descriptive explanation.

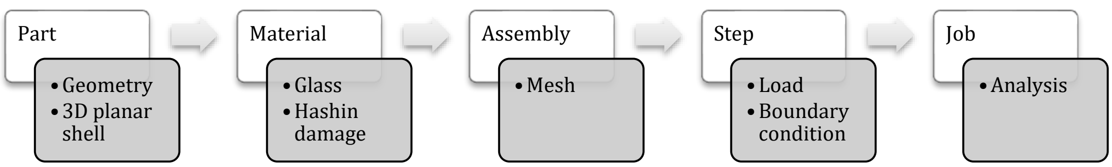

Figure 2: Procedural steps followed in Finite element solver "ABAQUS"

4.3.1 Part

The model of the FRP composite plate is built as a deformable 3d shell which has a geometry of 500X500 mm with varying thicknesses.

4.3.2 Material

All the FRP composite plates are made from Glass-epoxy, Model is treated as a conventional shell which will give the option to alter the composite fiber orientation in different layers. Layup of fiber inside a matrix creates a drastic change in the behavior of the plate. In order to have a good understanding of the buckling behavior four different layups were used in the analysis namely Unidirectional, 45° dominated, 0 dominated and Quasi layup. Layup other than quasi are treated as symmetrical layups. The use of word dominated refers to existence of higher number of certain layers compared to other. A common way to express orientation of a matrix is "$[90_x/\pm45_x/0_x]$", x denotes the number of ply's in the matrix. Each ply was chosen to have a thickness of 0.6mm, matrix order is chosen in such a way that overall thickness of all the model remain constant, total thickness is a product of ply count and ply thickness. "Table 1" shows the matrix order for available orientation and "Figure 3" shows orientations in detail.

Ply count	*8*	*16*	*24*	*32*	*40*	*48*
Thickness	4.8	9.6	14.4	19.2	24	28.8

Table 1: Thickness variation according to change in ply numbers

Orientation	***Matrix order***	***Ply count***
Unidirectional	$[0_x]_s$	4,8,12,16,20,24
$\pm$45° dominated	$[90_1/\pm45_x/0_1]_s$	1,3,5,7,9,11
0° dominated	$[90_1/\pm45_1/0_x]_s$	1,5,9,13,17,21
Quasi	$[[90_1/\pm45_1/0_1]_x]_s$	1,2,3,4,5,6

Table 2: Matrix orientation code with number of plies

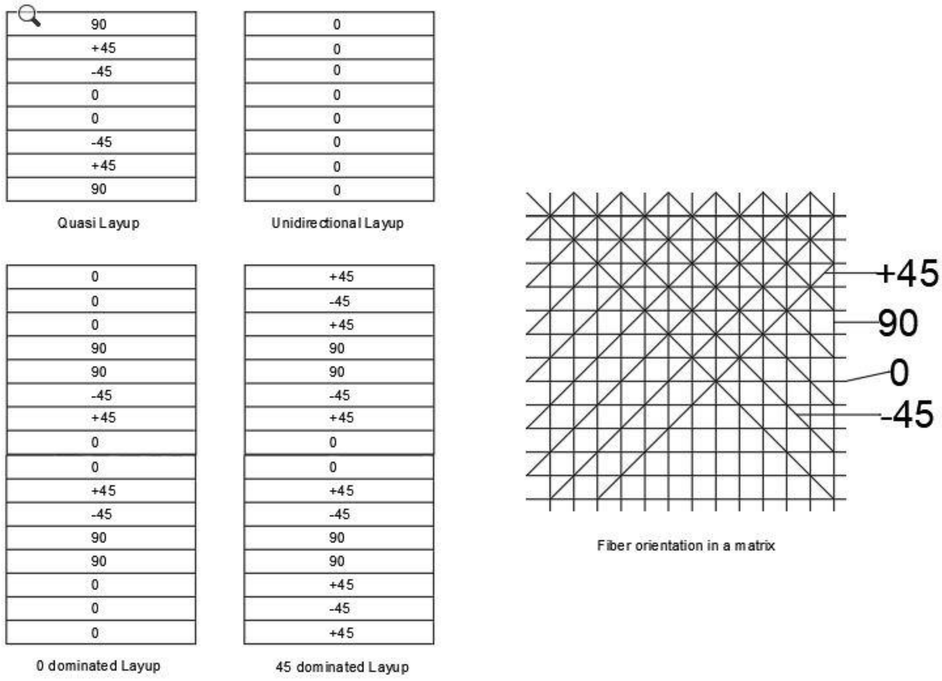

Figure 3: Fibre orientation in a matrix and Layup structure

To introduce a failure criterion "Hashin failure" is coupled with damage evolution. Unique failure analysis in matrix and fibers individually is achieved by choosing the damage evolution. Following table denoted all the properties of the Glass-epoxy composite which are obtained from Agarwal et al. (2018).

Property of Glass-epoxy	*Value*
Longitudinal tensile strength	1062 GPa
Longitudinal compressive strength	610 GPa
Transverse tensile strength	31 GPa
Transverse compressive strength	118 GPa
Longitudinal tensile fracture energy	1200 N/mm
Longitudinal compressive fracture energy	2700 N/mm
Transverse tensile fracture energy	17 N/mm
Transverse compressive fracture energy	25 N/mm
In-plane shear strength	72 MPa
Shear modulus (G_{12}, G_{13}, G_{23})	4.14 GPa
Poisson's ratio	0.26
Transverse modulus	8.27 GPa
Longitudinal modulus	38.6 GPa
Fiber volume fraction	0.45

Table 3: Material Parameter of Glass-epoxy

4.3.3 Assembly & Mesh

All the plate models are built as a single instance with four individual parts created by partitioning the plates, no position constraints are applied. Applied mesh has an approximate global element size of 40mm with a quadratic element shape. Curvature control and size control are left at default values. “Figure 5” and “Figure 4” shows the mesh and partitioning of the plate.

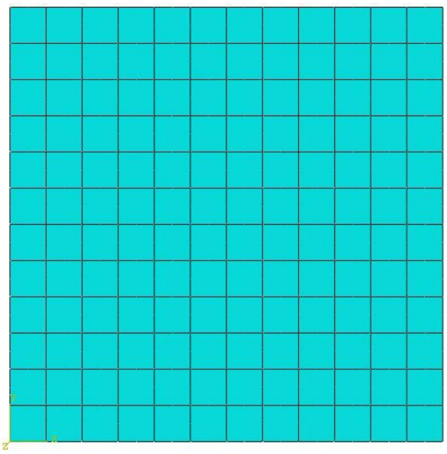

Figure 5: Mesh representation in FE model

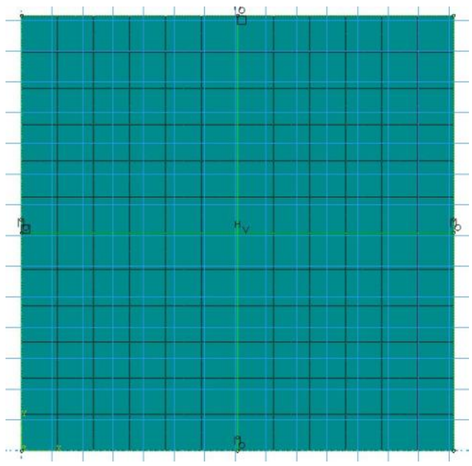

Figure 4: Representation of partition in the plate

4.3.4 Step

To run three different analysis on a single FE model three different step are created. First order buckling analysis is a linear analysis with the chosen step “buckle”. To introduce a buckle following line of code is added in the keywords section “NODE FILE, GLOBAL=YES, LAST MODE=1, U”. Last mode 1 represents the choice of targeting first eigen mode. Second order buckling analysis is a nonlinear analysis to perform the step is chosen to be “Static, General”. To introduce initial imperfection from the last analysis following line of code is added in the keyword section “ *IMPERFECTION, FILE=JOB, STEP=1, 1, 0.1” under the “ **STEP” section, last two numerals denote the targeted eigenmode and value of initial imperfection in millimeters. The difference in the first and second analysis is the choice of switching on the variable “Nlgeom” which represents the nonlinear geometry. For First order compression analysis chosen step being “Static, General” with Nlgeom off. Loads and boundary conditions are also applied while creating above mentioned steps. Following Table 4 represents imperfection factors used, “b” is the breadth of the plate.

Imperfection factors	*b/10000*	*b/200*	*b/100*
In millimeters	*0.05 mm*	*2.5 mm*	*5 mm*

Table 4: Initial imperfection in accordance with breadth of the plate

4.3.4.1Load & Boundary conditions

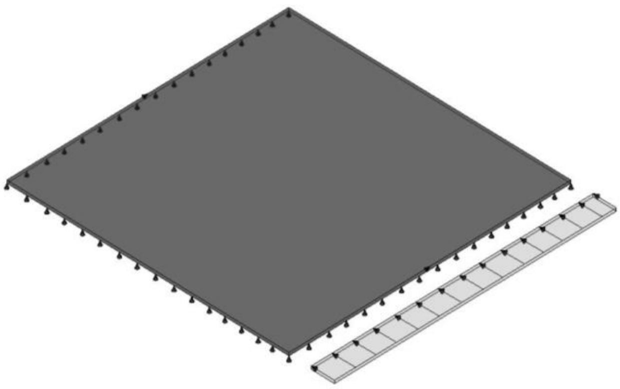

Figure 6: 3D model with loads and boundary conditions

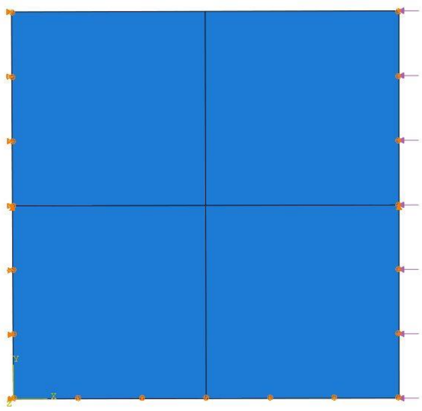

Figure 7: Actual plate from FE solve "ABAQUS"

Focus of this thesis was to analyze the effect of boundary conditions on a plate with uniaxial compressive load. “Figure 6” show a 3D representation of the FRP plate with all the boundary conditions and loading, “Figure 7” shows that actual FE model from ABAQUS.

Side	*Boundary conditions*
Top	X=0, Y=0, Z=0
Left	X=1, Y=0, Z=1
Bottom	X=0, Y=0, Z=1
Right	X=0, Y=0, Z=1

Table 5: Boundary conditions used in plate subjected to 3-sided support

Plate is simply supported on three side and restricted in X-direction on the left side in order to record the reaction forces created by the Displacement boundary condition on the right of the plate. To stabilize the plate two mid points on the left and right side of the plate are restricted in Y-direction.

Load are created from the displacement boundary applied on the right side of the plate, range of this displacement is 7mm and 12 mm for second order buckling analysis and first order compressive analysis, respectively. A normal shell edge load of 1000 KN is used just for first order buckling analysis to induce a buckle in the model.

4.3.5 Job

Every analysis requires its own job to output individual results, three jobs were created for first order buckling analysis, second order buckling analysis and first order compressive analysis. Every job is sent to perform a global targeted analysis with all the variable set at defaults values.

4.4 Results

A total of 72 plate models are analyzed to produced four groups of buckling curves each group representing a unique layup of fiber orientations. Six thickness are used to achieve decent slenderness scale for this study with three imperfection factors. To distinguish the models a proper notation is used.
For example, In the notation "G_Q_100_1", "G" represents the material Glass, Q represents the layup "Quasi", "100" represents the initial imperfection factor used, "1" represents first choice of thickness in total of 6 varying from 4.8mm to 28mm. All notations are expressed in Table

Name	*Notation*
Glass	G
Unidirectional	UD
0 dominated layup	0
45 dominated layup	45
Quasi layup	Q
Initial imperfection "b/10000"	10000
Initial imperfection "b/200"	200
Initial imperfection "b/100"	100

Table 6: Notations used to catalogue results

4.4.1 First Order Buckling analysis

First order buckling analysis results in Eigenvalue number needed for Equation (4.1) for the targeted buckling mode and Out of plane displacement showing the shape and placement of the buckle induced in the plate. “Figure 8” shows the direct output from ABAQUS software indication above discussed variables.

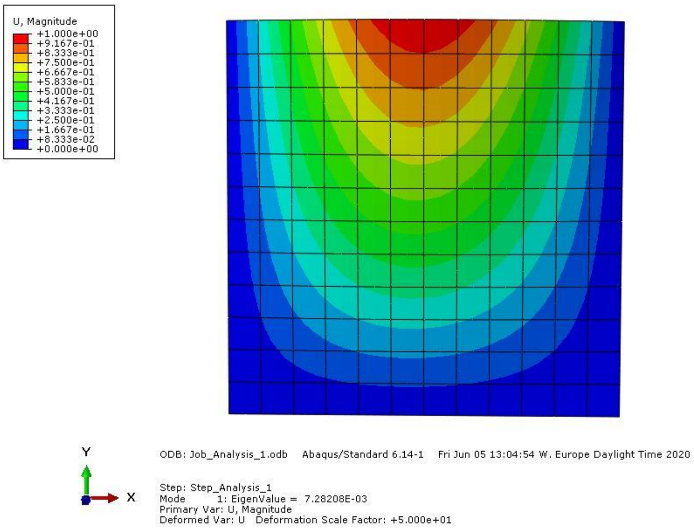

Figure 8: Buckling in 3sided FE model subjected to in plane compression.

4.4.2 Second order buckling analysis

Second order buckling analysis represents the buckling strength of the FRP composite plate as it reaches the maximum out a plane deflection with failure followed towards the end of the curve as seen in the “Figure 9”.

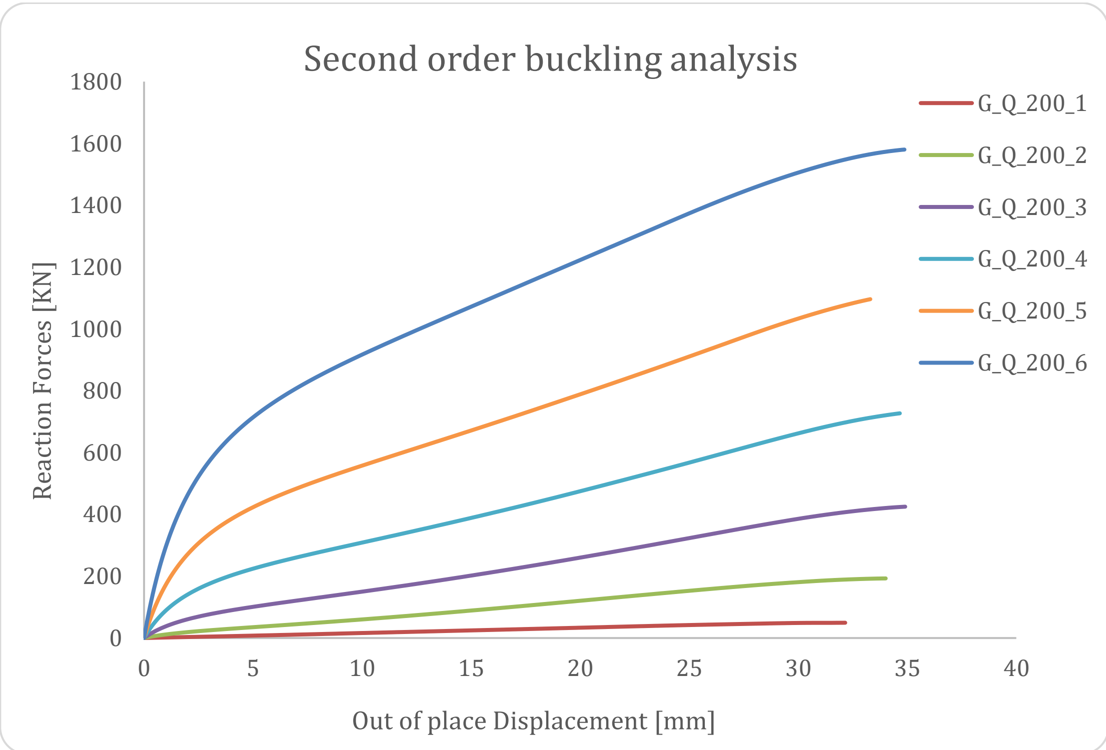

Figure 9: Reaction Forces VS out of plane deformation are plotted to represent buckling strength of the plate

4.4.3 First order compressive Analysis

First order compressive analysis results in finding the ultimate compressive strength of the FRP composite plate. Ultimate compressive strength of the plate changes with Layups of the plate, but its rests well within both transverse compressive and longitudinal compressive strength limits. "Table 7" shows the range of compressive strength across all the layups.

Thickness (mm)	*Quasi Layup Ultimate strength (MPa)*	*0 dominated Ultimate strength (MPa)*	*Unidirectional Ultimate strength (MPa)*	*45 dominated Ultimate strength (MPa)*
4.8	262	262	610	262
9.6	262	437	610	184
14.4	262	495	610	168
19.2	262	524	610	160
24	262	541	610	155
28.8	262	553	610	152

Table 7: Variation in ultimate strength according to layup difference and change in thickness

4.4.4 Buckling Curves

Non-dimensional slenderness and Buckling reduction factor were drawn against each other to build these Buckling curves. Profound effect of slenderness on the buckling behavior of a structure led to the birth of this buckling curve concept.

The selected layups respond drastically different used uniaxial load when compared side by side, 45 dominated layups being the best suitable layup followed by Quasi dominated and 0 dominated with 45 dominated being the least suitable layup for considered uniaxial loading. Figure visualizes buckling curves for all the 72 models. Slenderness of the plate decreases as the graph moves to the right and reduces towards zero indicating stocky plates needs no reduction in loading. None of the buckling curves reach value "1" in terms of buckling reduction factor indicating the significant effect due to the presence of a free edge, "Figure 10" represents all the buckling curves. Individual buckling curves are show in "Figure 11", "Figure 12", "Figure 13", "Figure 14" respectively.

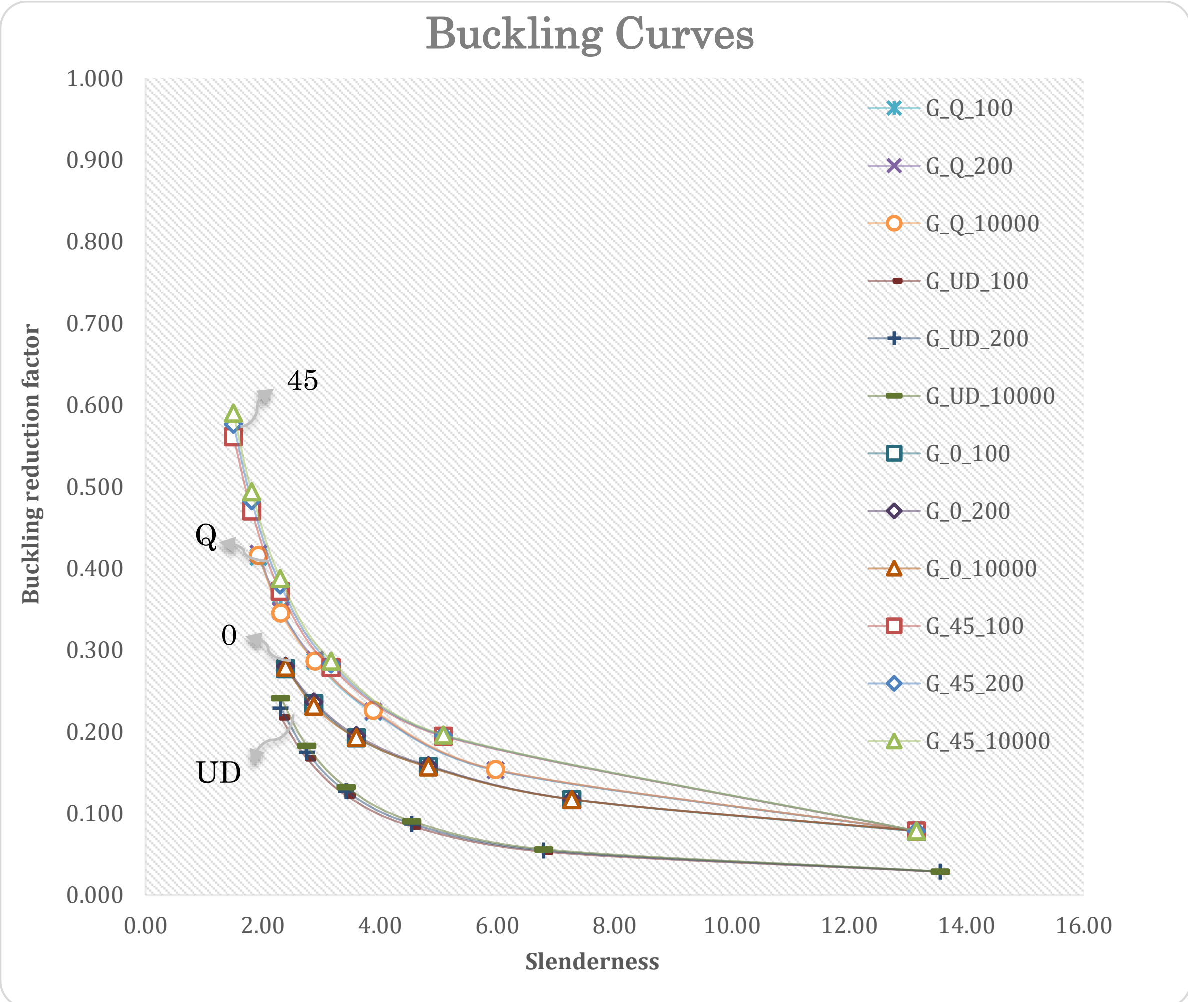

Figure 10: Buckling Curves of 72 plates with 4 layups, 3 initial imperfection factors.

Unidirectional layup is the worst choice under uniaxial loading with the least buckling reduction value, more than 75% of the load must be reduced under considered circumstances for the plate. Increase in thickness leads to a visible spread in the curves with different initial imperfections.

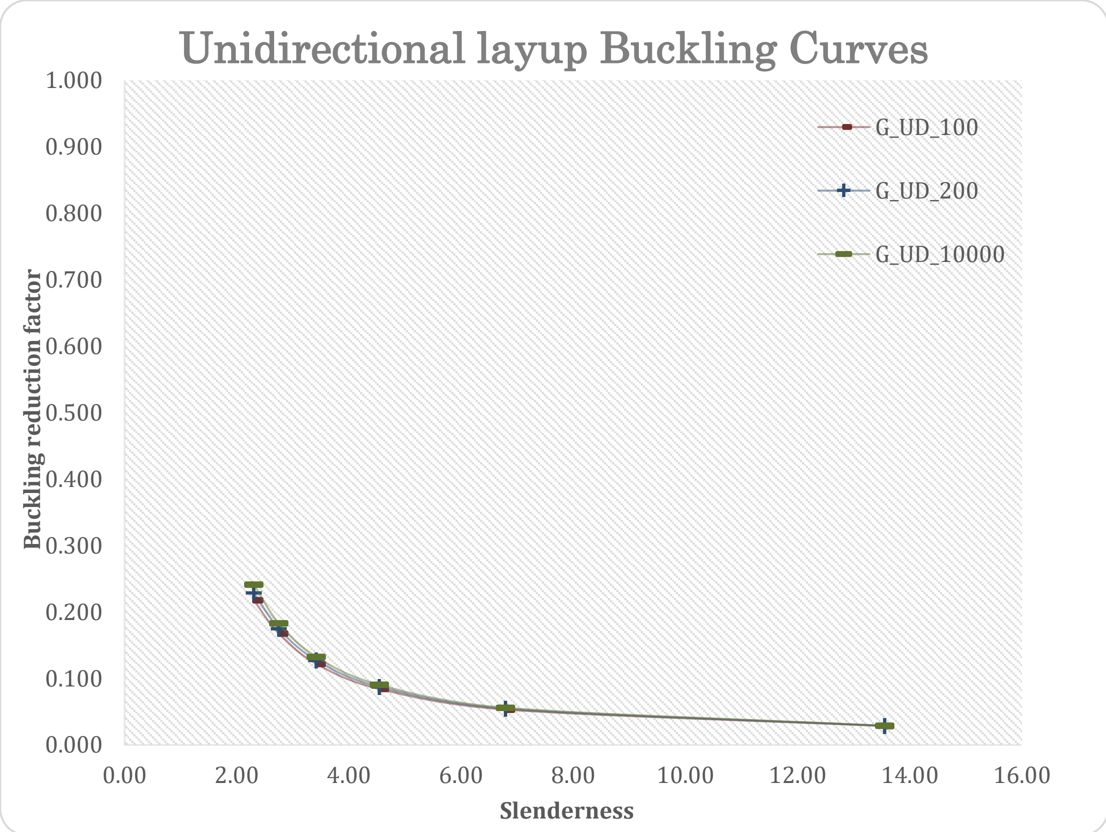

Figure 11: Buckling Curves of Unidirectional layup.

45 dominated layups are the best choice under uniaxial loading with the highest buckling reduction value, less than 40% of the load must be reduced under considered circumstances for the plate. Increase in initial imperfection lead to further decrease in buckling reduction factor in stockier plates.

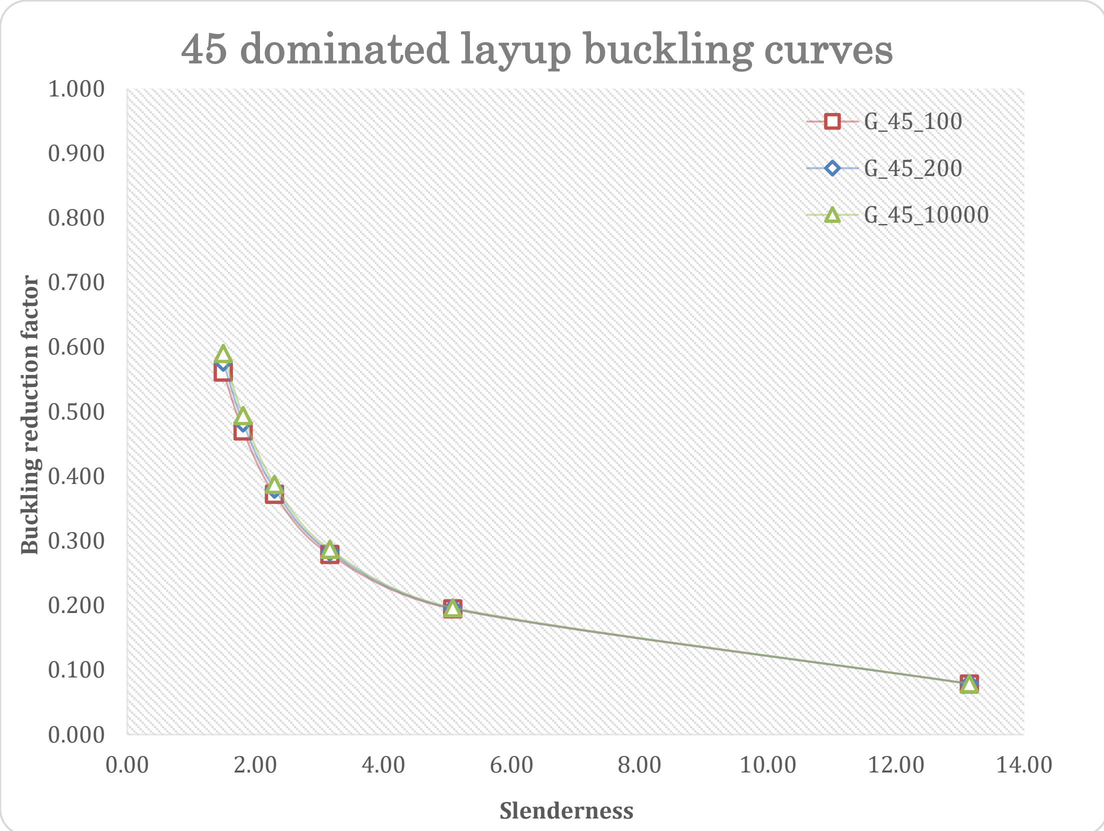

Figure 12: Buckling Curves of 45 dominated layup

0 dominated layup is the third-best choice under uniaxial loading with the lowest buckling reduction value, more than 70% of the load must be reduced under considered circumstances for the plate. Increase in initial imperfections seems to have little to no effect on the reduction factors.

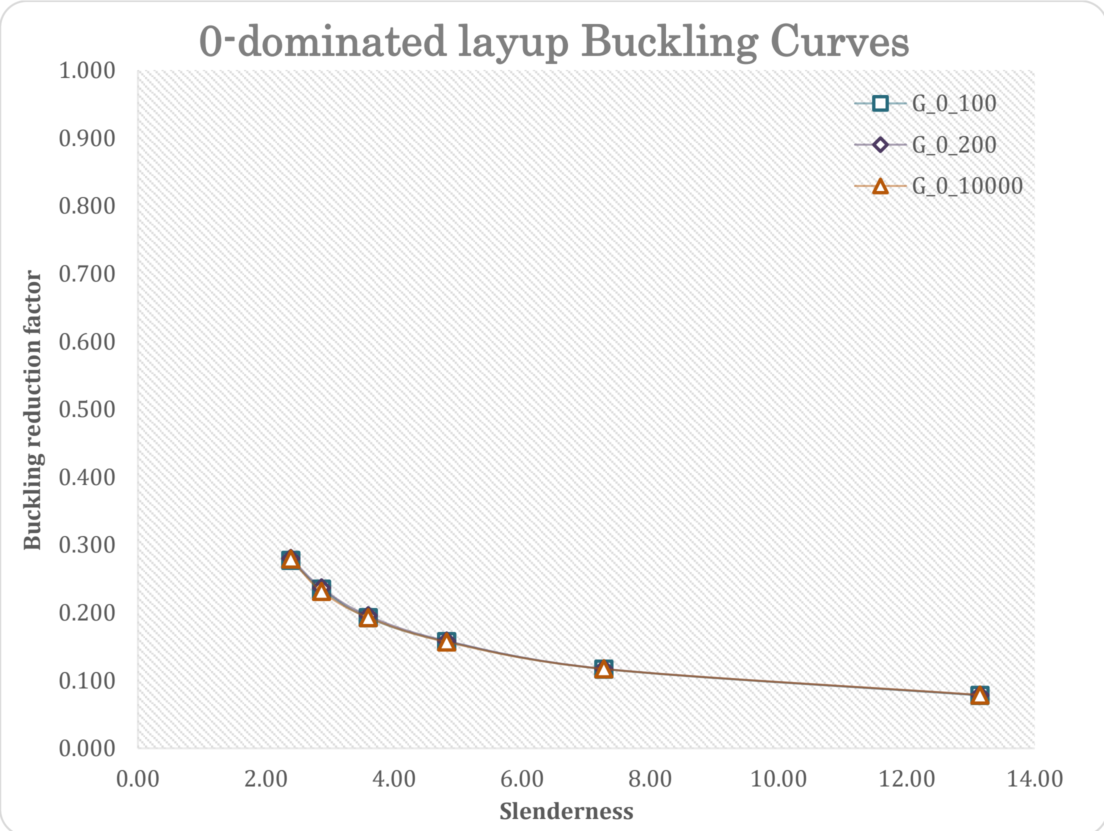

Figure 13: Buckling Curves of 0 dominated layup

Quasi layup is the second-best choice under uniaxial loading with a significant buckling reduction value, more than 42% of the load must be reduced under considered circumstances for the plate. Increase in initial imperfections seems to have little to no effect on the reduction factors in this layup too.

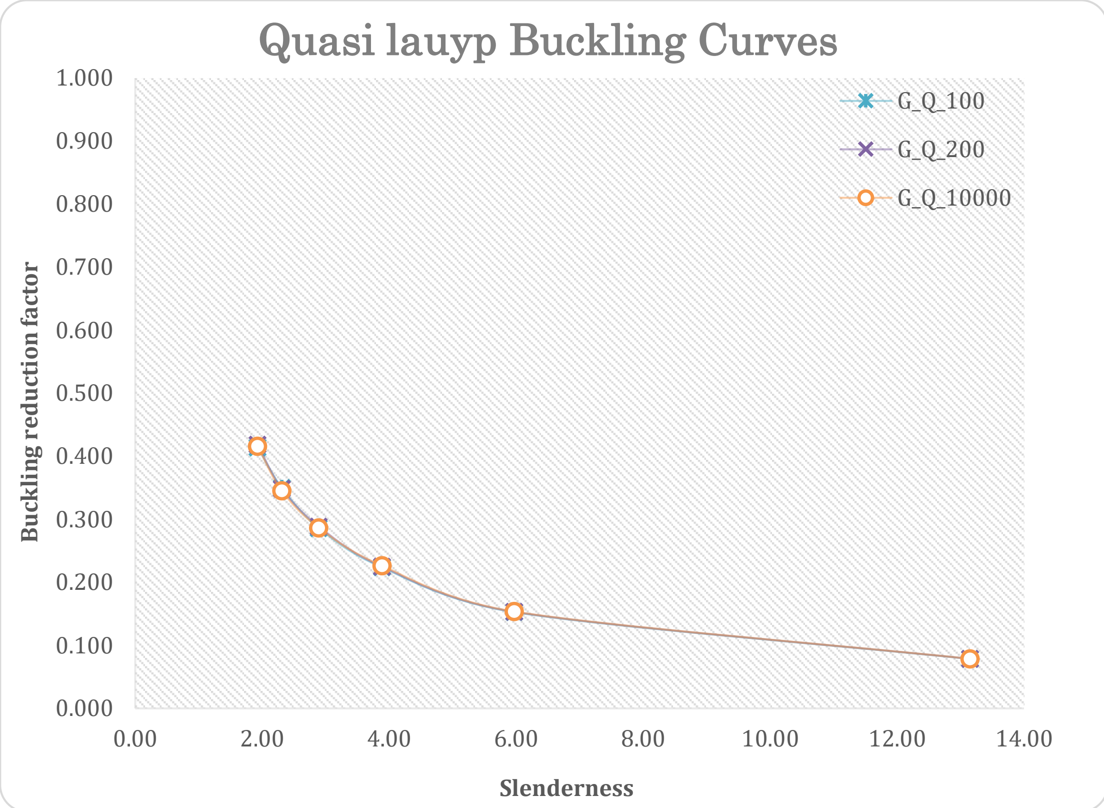

Figure 14: Buckling Curves of Quasi layup

5 Buckling behavior of FRP composite plates with hole

An FRP composite plate with a 100mm diameter hole placed at the center is analyzed in Finite element solver software named “ABAQUS”. This chapter represents the methods used to analyze the buckling behavior and evaluated results from the analysis.

5.1 Methodology

Study of buckling behavior in FRP composite plates with a hole follows similar methodology as the previous composite plate in chapter 4, python scripts are used to create 72 model with similar configuration as in chapter 4 with an exception of boundary conditions and introduction of a hole into the plate.

5.2 Description & formulation

This chapter follows the same exact approach in the analysis as chapter 4, the purpose of this chapter is to study the impact of hole in the plate, in order to analyze all the 72 models some limitation has been placed to understand and to reach a conclusion with the results. Geometry of the hole is restricted to be of a single value of 100mm and change in placement of the hole is limited meaning that only plate with a hole in the center has been studied.

5.3 Finite Element Model

All 72 FRP composite plate models are modelled in “ABAQUS”, the plate is simply supported on all four edges, with X-direction restricted on the opposite of the load to record reaction forces and Y direction is restricted at mid-point on left & right side of the plate to maintain stability. Similar layups, thicknesses, imperfection factors and material properties from chapter 4 are used in this analysis.

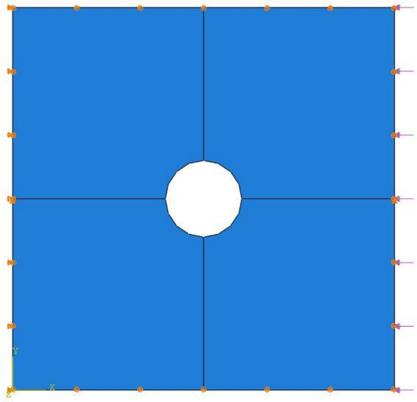

Figure 15: Actual plate from FE solve "ABAQUS"

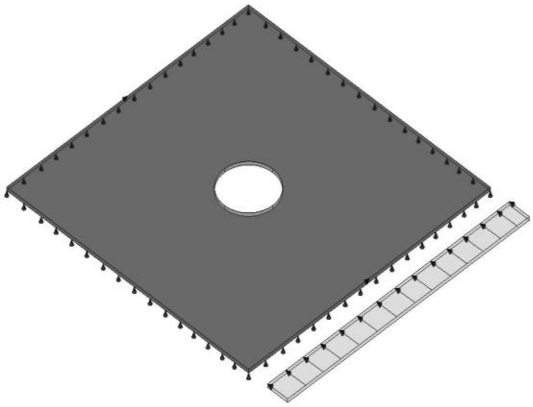

Figure 16: 3D model of plate with hole in the middle

This model has 2 changes compared to the previous model in chapter 4, one on the is boundary condition. "Table 8" represent the new boundary conditions.

Side	*Boundary conditions*
Top	X=0, Y=0, Z=1
Left	X=1, Y=0, Z=1
Bottom	X=0, Y=0, Z=1
Right	X=0, Y=0, Z=1

Table 8: Boundary conditions used in plate with hole in the centre

The distribution of the mesh and portioning has a slight due to the presence of the hole at the center. The plate is now meshed on parts rather than meshing on instance. "Figure 17", "Figure 18" pictures the differences.

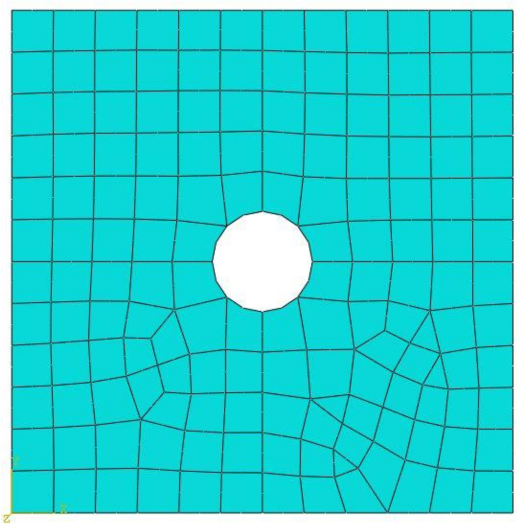

Figure 17:: Mesh representation in FE model

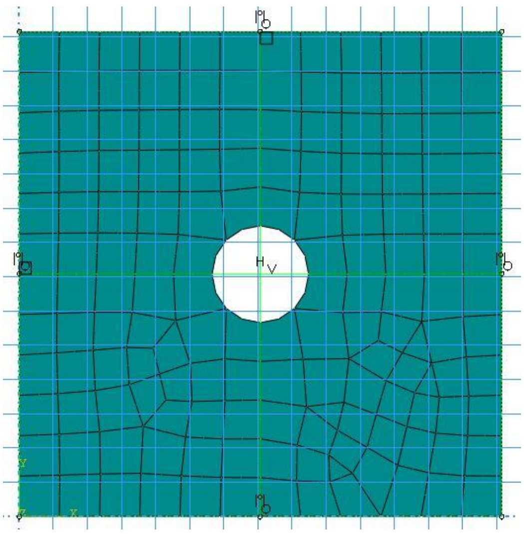

Figure 18: Partition representation in FE model

5.4 Results

A total of 72 plate models are analysed to produced four groups of buckling curves each group representing a unique layup of fibre orientations. Six thickness are used to achieve decent slenderness scale for this study with three imperfection factors. In order to distinguish the models a similar notation from chapter 4 are used, the letter “h” in the notation mentions the presence of hole in the plate.

5.4.1 First order buckling analysis

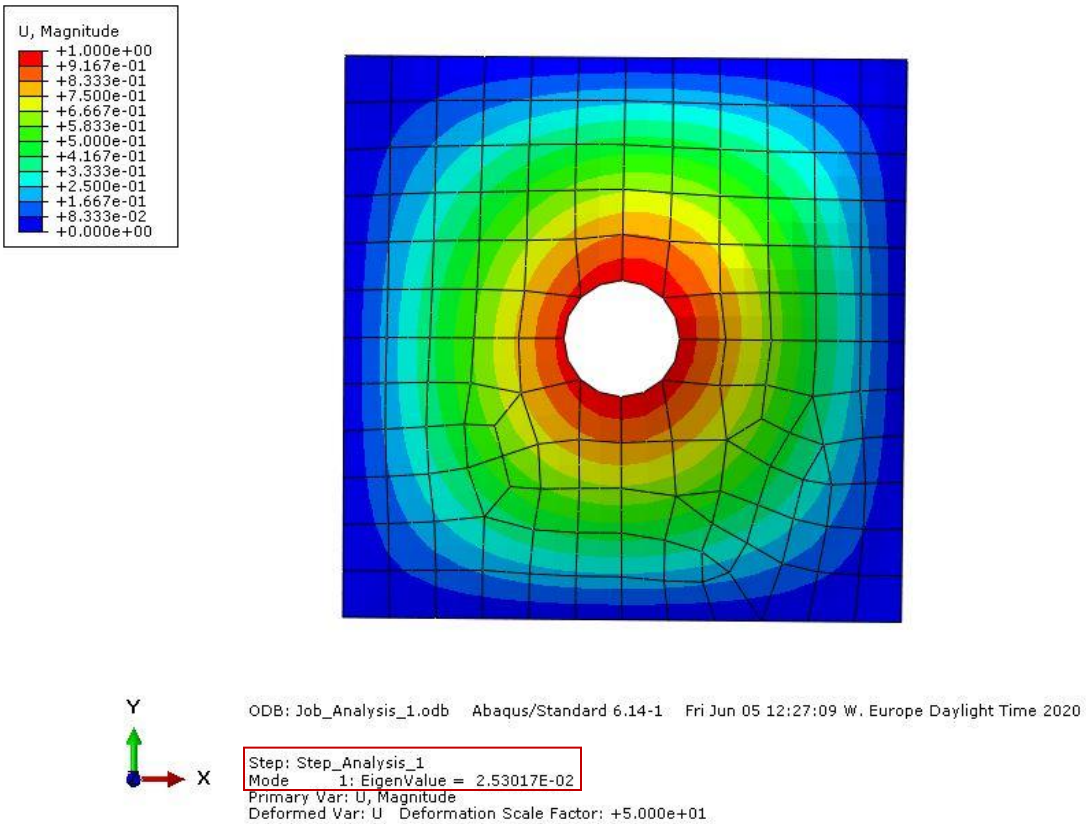

Figure 19: Buckling in FE model with hole in the centre and subjected to in plane compression.

To calculate equation 4.1 eigenvalue is needed, first order buckling analysis give out the necessary eigenvalue, Eigenvalue is directly is directly taken from “ABAQUS”, it is highlighted in “Figure 19”.

5.4.2 Second order buckling analysis

From second order buckling analysis a graph with reaction force against out of plane displacement is produced to study the buckling strength of the plate and total deflection resulted by the maximum buckling force. From the graph it is observed that stockier plates tend to buckle significantly less than slender plates at a lower reaction force.

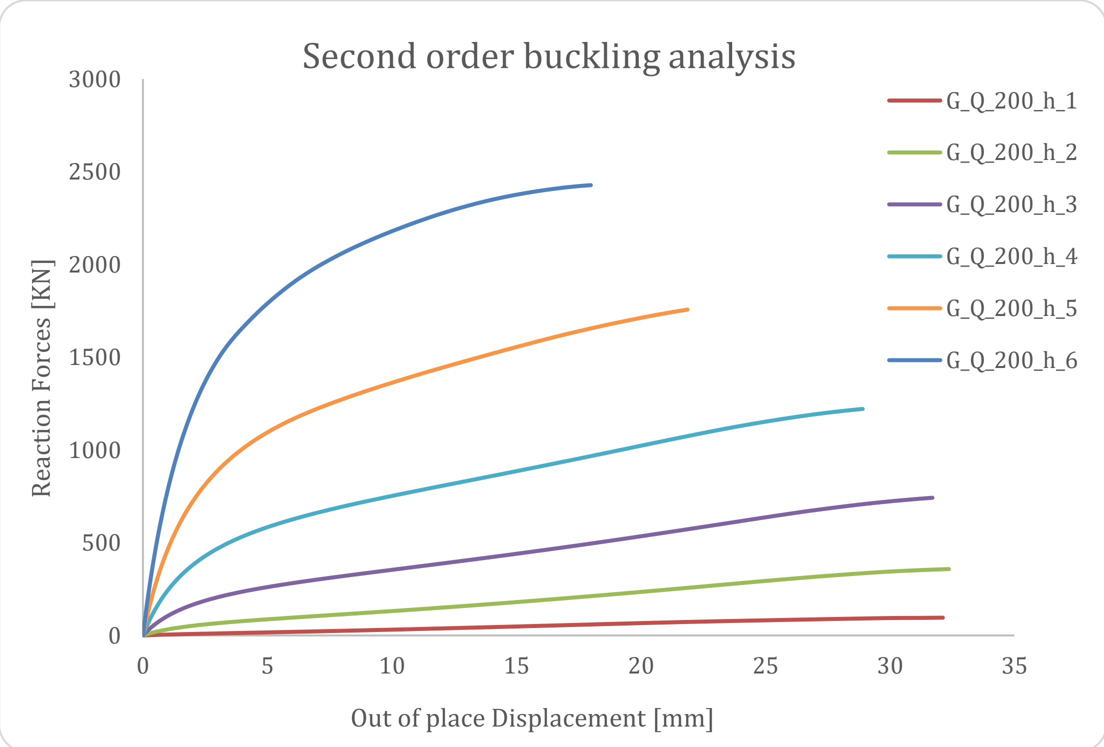

Figure 20: Reaction Forces VS out of plane deformation are plotted to represent buckling strength of the plate

5.4.3 First order compressive analysis

Since first order compressive analysis depend on the properties of the materials the results of ultimate buckling strength from this analysis remains same as chapter 4.4.3

5.4.4 Buckling curves

Buckling curves are developed by plotting slenderness and buckling reduction factors against each other, slenderness and buckling reduction factors are obtained from "Equations 4.4 & 4.5". All the layups tend to have similar slopes compared to the plate in chapter 4 with minor differences in values. Layups from worst to best “UD”, ”0-dominated”, “Quasi”, “45-dominated”. “Figure 21” visualizes buckling curves for all the 72 models. Slenderness of the plate decreases as the graph moves to the right and reduces towards zero indicating stocky plates needs no reduction in loading. None of the buckling curves reach value “1” in terms of buckling reduction factor indicating the significant effect due to the presence of a hole in the plate. Individual buckling curves are show in “Figure 22”, “Figure 23”, “Figure 24”, “Figure 25” respectively and response of curves are similar curves in “Chapter 4”.

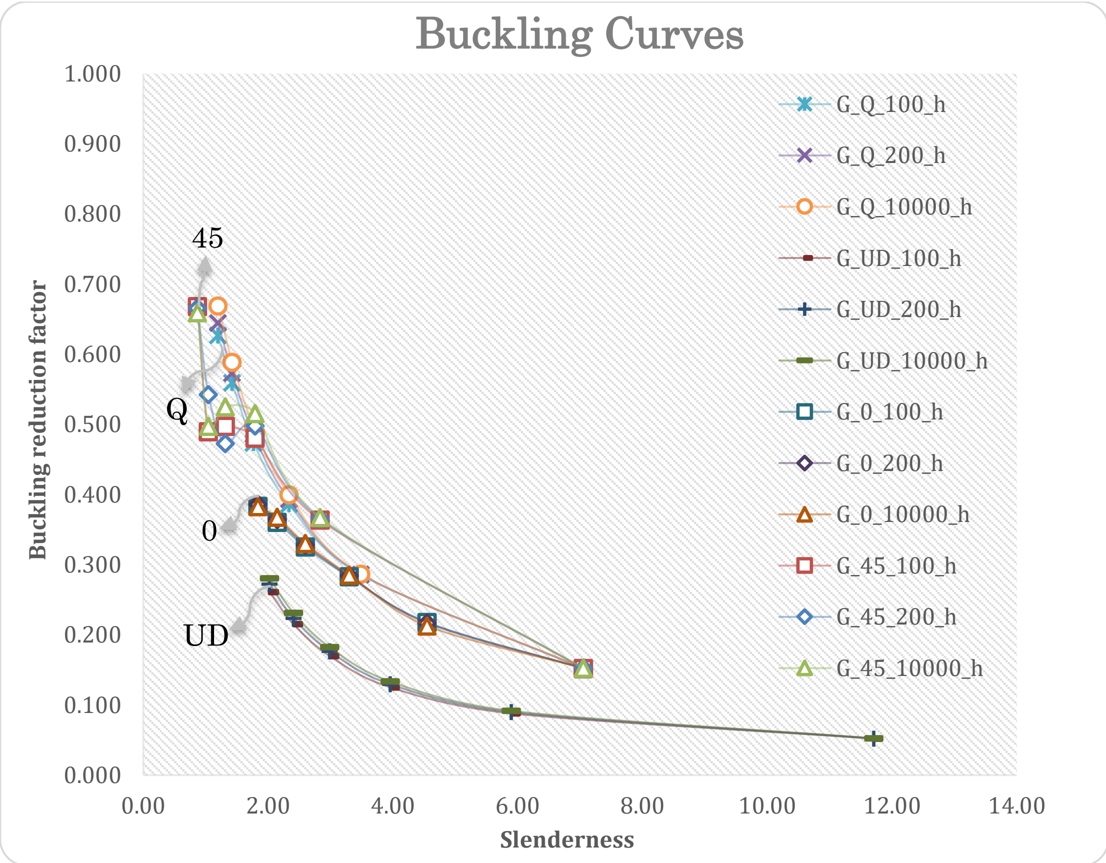

Figure 21: Buckling Curves of 72 plates with 4 layups, 3 initial imperfection factors.

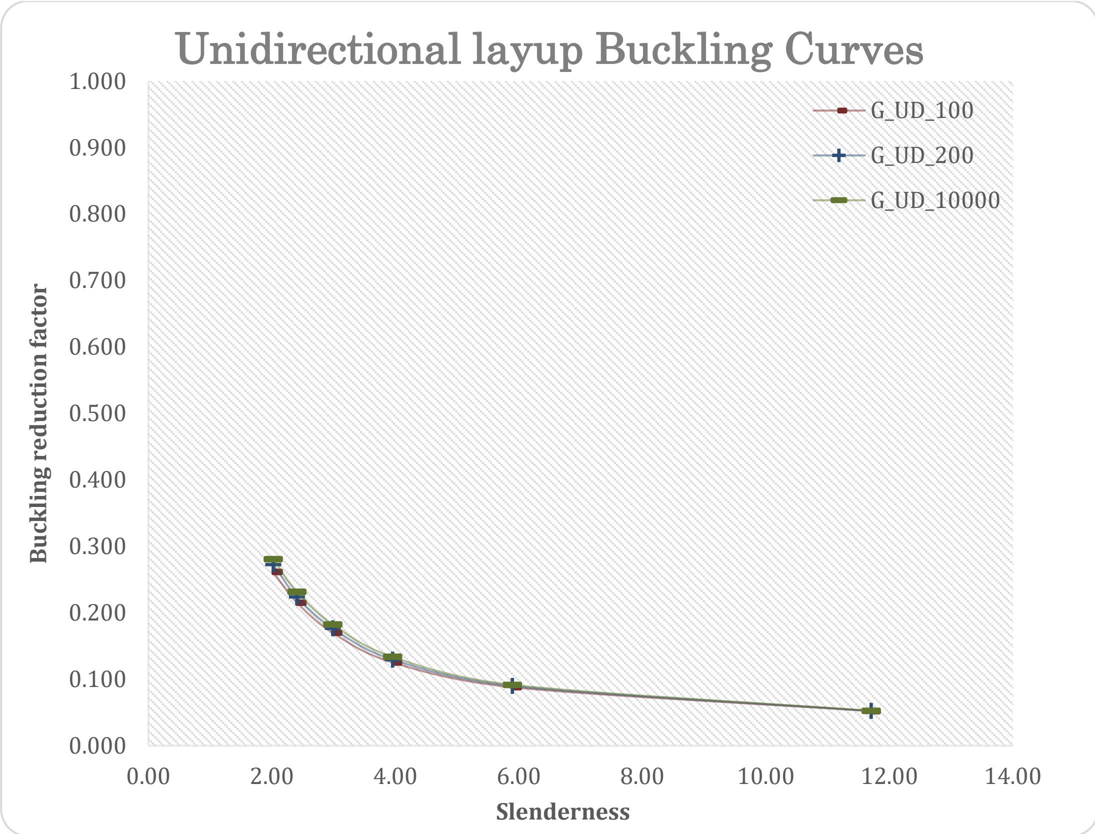

Figure 22: Buckling Curves of unidirectional layup

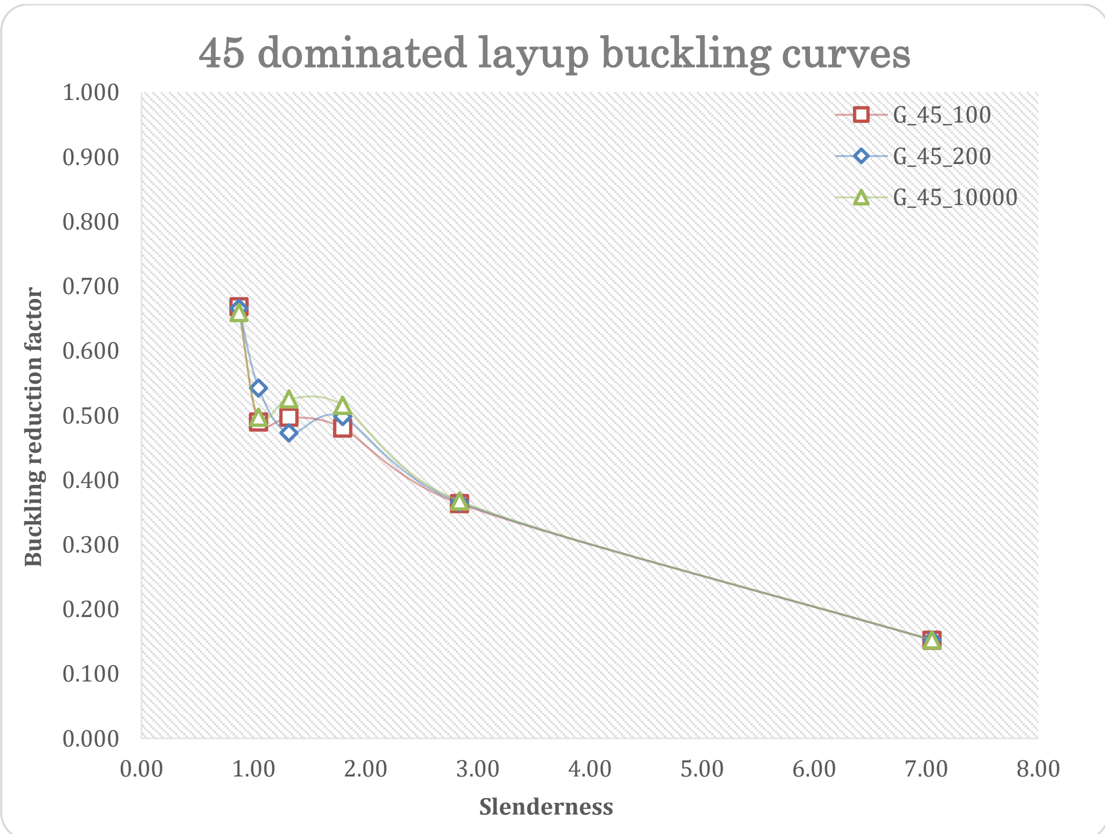

Figure 23: Buckling Curves of 45 dominated layup

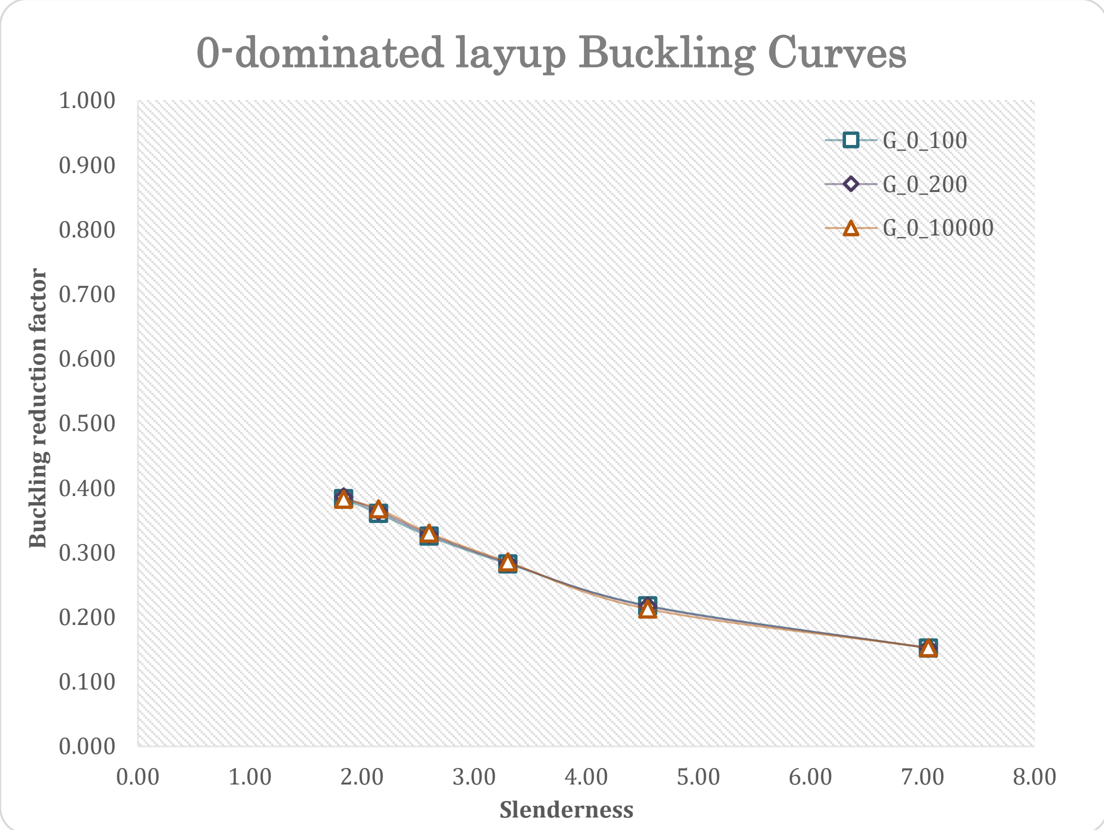

Figure 24: Buckling Curves of 0 dominated layup

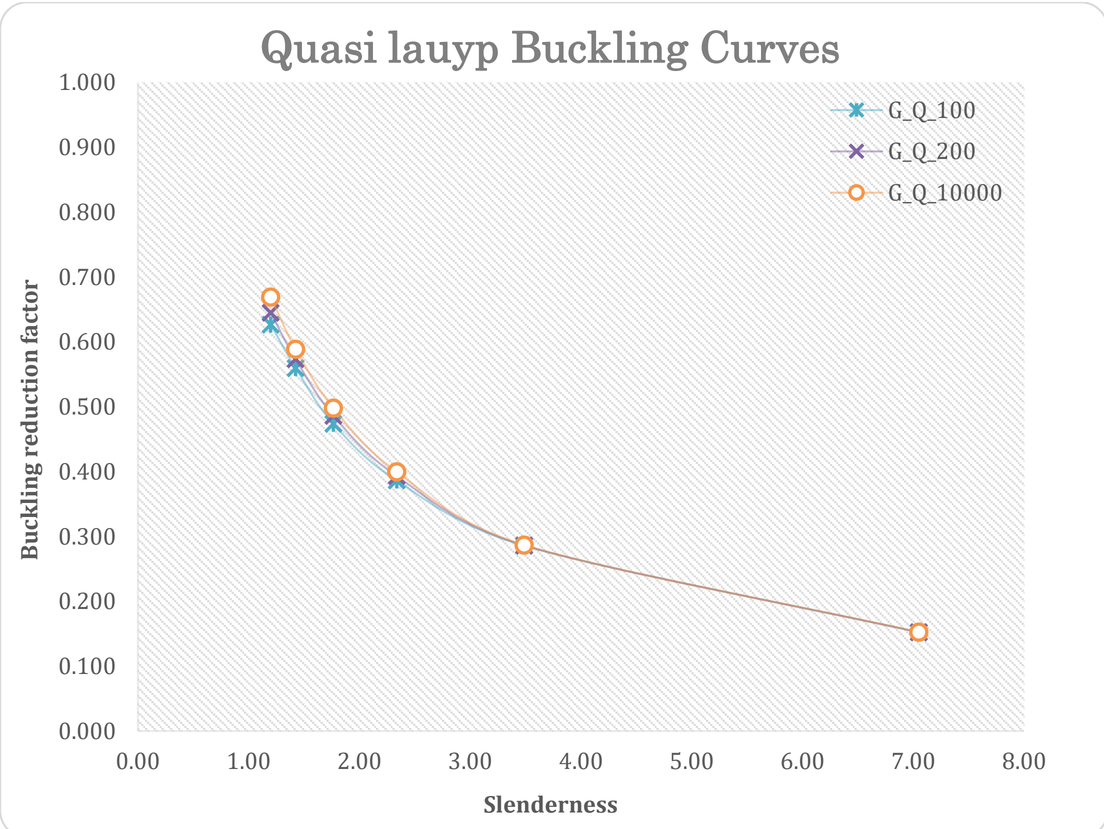

Figure 25: Buckling Curves of Quasi layup

6 Discussion

The objective of this thesis is to perform a study of buckling behaviour of FRP composite plates subjected to various boundary conditions, imposed imperfections with various variables and thicknesses under a uniaxial compressive load. Such study involving vast variations in different variables created an exposure to get that much close for mastering the behaviour of FRP composite material. Below is a short overview of the work done in the thesis.

Two FRP composite plates made from Glass-epoxy material are analysed for buckling behavior, Four unique layups, Six thicknesses, two different boundary conditions and one plate with a hole in the centre. Significant effect in buckling behaviour is noticed in the accumulated results are seen due to change in the layup used in the plate. In order to perform a through study of all these variables some limitations had to be introduced, the position of the hole in the plate was designated to the centre, loading on the plate in only applied in uniaxial direction and set to be uniform, change in boundary condition was only restricted in Z direction, Range of imperfection factors were kept small since the effect of it noticed only in stockier plate with multi directional layups was enough for this study. As far as the results go the first order analysis in "ABAQUS" simulated an expected out of plane deformation when a free edge is presented, from the second order buckling analysis in the "Figure 9" reaction forces vs out of displacement it is seems that the stockier plates can resist higher loads under higher out of plane deflection when compared to the slender plates proving a nominal behaviour, lastly from the first order compressive analysis the ultimate strength of the plate is achieved for all the available six thicknesses as seen in "Table 7" the values of the ultimate strength doesn't exceed the actual longitudinal compressive and transverse compressive strengths of the Glass material this further validates the analysis and the results obtained.
This ultimate compressive strength change with the change in layup of the plate, as the 0° dominated plies increase the ultimate strength increases, Unidirectional plies improves the ultimate strength of the plate to the maximum limit since the load is carried uniaxially along the length this effected can also be seen in 45° dominated layup that is as the number of unidirectional plies are dominated by 45° piles the load are no longer carried uniaxially thus reducing the ultimate strength of the plate. "Figure 10", represent the curve approach towards unity as the becomes more stockier and as the slenderness of the plate increases the buckling reduction

factor values falls towards zero demonstrating that higher the slenderness higher reduction in loads and vice versa.

“Figure 10” shows a correlation in thickness, imperfection factors and buckling reduction factors. The effect of imperfection factor increases with increase in thickness of the plate, that is stockier plate are more susceptible to imperfection factors than a slender plate. From the same figure it is observed that the buckling reduction factor is reduced with the increase in the initial imperfection in the plate. This again change with specifics of the layup used in the plate, 0° dominated layup doesn’t have a significant effect due to the initial imperfection factor where in 45° dominated and Unidirectional layups a clear shift in the buckling curve is noticed. Failure in the plate is dominated by the material of the fibre rather than the resin used to bind the fibres in matrix so all the behavior criteria must be focused on the material used for the fibres. One unclear behaviour noticed in “Figure 10” is that the buckling reduction factor of the slender plates using a layup other than a unidirectional layup tend to approach similar values, this phenomenon is not expected, and reasons are unclear as this only happens in the slenderest plates.

Presence of hole in the plate has similar buckling behavior as the plate with a free edge, “Figure 21” shows that the buckling reduction factor value of a plate with a hole has lower bound values compared to the plate with a free edge, Thickness, initial imperfection factors, distribution of layups all these parameters in FRP composite plate with a hole behaves in a similar way compared to plate with a free edge, only distinction between these two plates is that the plate with free edge need higher load reduction than the plate with a hole.

7 Conclusion

The thesis emphasizes on contribution to the study on design and behaviour of thin walled FRP plates for structural engineering applications. It involves a substantial research on the state-of-art literature and existing experimental data on the buckling behaviour of thin walled FRP plates subjected to in-plane compression loading. Based on the knowledge gained from the state-of-art research, a parametric study was carried out to analyse thin walled FRP plates subjected to in-plane compression loading with variable boundary conditions, multiple layups, different imperfection factors, width-to-thickness ratios, consideration of presence of a hole.

The Pre-study of the existing work familiarized the authors with the usage of FEM analysis for FRP members and to understand the methodology used in the prospective technical specification document for future Eurocode. The results from the parametric analysis holds scope for several key interpretations. Out of all the considered parameters, the combination of layups in the plates is the major influence on the buckling curves or the buckling behaviour. The non-dimensional slenderness of the plate is guided by the imposed boundary conditions. In stocky plates, the effect of initial imperfections on the buckling reduction factor is evident. Even though the buckling curves for the plate with the hole draws same path as of a plate without a hole, the critical loading capacity of a plate with a hole is around 10% lesser than the one without the presence of a hole.

8 Scope for future study

The study has resulted with the fair number of conclusions going into the future. As the future Eurocode needs to have technical specifications for all the possible variabilities in the material and performance of the plate, the scope for further research is predominant. The authors are optimistic about the contribution of the current thesis work in developing standards for the buckling behaviour of FRP composite plates.

The state-of-art study on the buckling behaviour indicates that the buckling behaviour of FRP plates are designed based on lower bound approach which is safe. The inclusion for the effect of Post-buckling strength in the theoretical design for the stability of FRP plates. The parametric study has the wider scope with the possibility of obtaining data based on the consideration of several parameters such as material properties, aspect ratio, thickness-to-width ratio etc. In terms of loading criteria, the studies regarding behaviour of thin walled FRP plate when it is subjected combined compression and bending, shear loads, out-of-plane loads is important. A study on the effect of shifting eccentricity of the hole and multiple holes on the buckling behaviour of the plate will be interesting. The parametric study on buckling behaviour of FRP plates subjected to bi-axial compression loading and assessment of the results against the uniaxial compression loading would be enticing.

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