COMPOSITE PLATE OPTIMIZATION WITH STRUCTURAL AND MANUFACTURING CONSTRAINTS

by

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Dedication

This thesis study is dedicated to my parents Dr. V.N. Prasad Polaki and Mrs. Meenkashi Polaki, my sister Divya Polaki for their unconditional love and support throughout my life.

I would like to thank Gajendra Gangadara and Sitanshu Pandya for their help and suggestions throughout my research work. I also would like to thank my dear friends Bharathi Bhattu, Nikhil Bhogaraju, Ashish Raghupatruni, Krishna Ritvic Viriyala, Maithri Vemula and many others for their encouragement throughout my academic life.

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Abstract

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This is design optimization study that focuses on the value of free size optimization technology on composite structures which incorporates realistic structural requirements and practical manufacturing limitations to achieve an iterative design with effective structural performance. To detail a study on such practical implementation, a sample structure is required. A rectangular composite laminate with a central hole cutout is considered for this study and is designed using finite elemental tools which includes compression, tension and shear loading conditions with load reactions at bolted joints and buckling stability. Free size optimization and size optimization are used in this study to design this laminate and compared with a conventional three zone laminate to estimate the structural integrity of the designs. Various design constraints are implemented that includes static strength, damage tolerance, structural stability, bearing-bypass criteria at bolted joints and manufacturing constraints in this study involves ply drop off effect and tow dimensional limits to reduce ply shape complexity, increase manufacturability and subsequently reducing manufacturing cost. Ply ramp rate effect and ply drop effect are studied by investigating the results with various values, ply dimensions and layout are simplified by implementing a set of rules that induce suitable dimensional limits.

TABLE OF CONTENTS

List of Illustrations

List of Tables

INTRODUCTION

The method to design a product that satisfies the objective under certain conditions or constraints is called Design Optimization. The modern methods of design optimization in the finite elemental methods have enabled weight minimization and accelerated maturation of structural design concepts that more readily satisfy margin-of-safety calculations during subsequent detailed analysis. To generate a reliable and robust design, the optimized model must be accounted to satisfy all constraints under certain loading environment. For composite structures, the treatment of loading conditions is different in comparison with isotropic metallic structures. The design criteria to be applied for composite structures include static strength, stability, damage tolerance, bearing-bypass strength at bolted joints and manufacturing constraints. Misguided or Incorrect designs may be formed if any of the above-mentioned conditions are missed or miscalculated.

Traditional optimization of composite structures results in ply thickness and sizing, recent advances in the optimization techniques enabled free size optimization which enabled in optimal design of ply shapes which helped in saving weights of the product by creating highly tailored shape of each ply under suitable loading environment. However, to maintain the complete constraint and load environment satisfaction, the level of sensitivity of the optimal design increases to a higher level. Additionally, Ply shape complexity increases the manufacturing effort which substantially increases manufacturing cost. To determine the value of using optimization technology to design ply shapes as part of an overall composite component design process, optimal designs must be compared to baseline designs using conventional methods and a full range of realistic design criteria. This study determines the potential weight improvement benefits that can be gained from shaping plies using finite element based composite free-size optimization and measures these improvements against the cost of increased ply and laminate complexity. The previous study focused on comparison of methodologies through application of a full range of composite design criteria, which included static strength, stability, damage tolerance, bearing-bypass strength at bolted joints, and some manufacturing constraints (ply percentage, symmetry, and consecutive ply count). The present work expands on the previous study[1,42] to include additional manufacturing constraints for ply drop rate and ply shape complexity. The applied manufacturing constraints assume that advanced fiber placement technology is used for component fabrication.

This study discusses the background of the composite structural optimization of a composite laminate, the design required, equations and tools required to implement the structural and manufacturing constraints of the laminate. Next, it discusses the implementation of tow dimensional constraints on each ply and the implementation of the rules required to manufacture all the plies that have been extracted after free-size optimization. Finally, the paper shows various outcomes extracted from size optimization by varying pressure loads and Plydrop constraints. These results of optimal designs are compared to traditional plies to weigh out the importance of optimization. The illustrations shown below are the examples of the designs from traditional optimization and three phase optimizations.

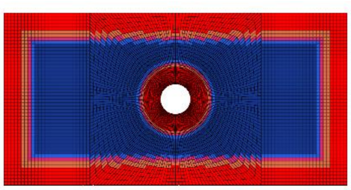


Figure 1: composite laminate derived from traditional optimization process

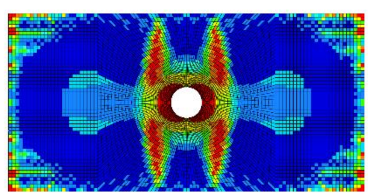


Figure 2: composite laminate derived from three phase optimization process

2. BACKGROUND

This thesis study is a continuation of "Comparison of Methodologies for Optimal Design of a Composite Plate under Practical Design Constraints" by Dr. Robert Taylor, John Strain and Admani[1]. Further investigations and comparisons with additional practical design and manufacturing considerations were included in this study[42].

2.1 Manufacturing of Composite Materials

Composite materials are the combination of two or more materials together with compositions on a macro scale. Each layer can be made of different materials like fiberglass, carbon fiber, graphite, etc. Different kinds of composite materials like unidirectional, multidirectional, short fiber composites, and particle reinforced composites are used for different sets of applications[2]. This study focuses on unidirectional composites in which each layer (ply) which contains woven fibers aligned in a specific direction and angle is combined with other layers. Each layer/ply has its own isotropic property based on the direction of the fiber alignment. A bonding agent is applied on each layer or in some cases prepreg are used to bond the layers to form a laminate. This laminate is then cured in an autoclave to harden the bonding agent. Intimate knowledge and high level skills are required to manufacture composite material products[2]. Manufacturing methods can either be manual or automated and can be classified based on various factors. Some commonly used manufacturing processes are Resin Transfer Molding, Open Molding, Resin Infusion Molding, Compression molding, Filament winding, Pultrusion, Tube rolling, Automated fiber placement, Automated tape laying, Centrifugal casting, and Hand layup. Typically, the selection of manufacturing process is dependent on the design and structural analysis used on the composite part.

2.2 Design Optimization

The goal of any design is to attain the best possible structural configuration with respect to the requirements of the job. The definition of the perfect design varies from one design problem to the other. For example, a perfect design of the stiffener on a boat is expected to have maximum stiffness or a perfect design of a car chassis will be judged to have less manufacturing cost, minimal weight, durability, etc. As discussed by Robert M. Jones[3], the criteria of each design vary with the goal set. In optimization terms, the goals that are to be achieved are mentioned as objective functions. More often in complex mathematical problems, multiple objectives for a single design can be assigned but the objectives cannot be maximized or minimized together at once or contradict each other.

The objective function being the ultimate endpoint to achieve, there are certain parameters that influence the design to result in a positive outcome. In optimization terms, these parameters are called design variables and constraints. R. T. Haftka and Z. Gürdal[5] mentioned in their work that improvisation of a structure can be possible by implementing design freedom on the structure. This potential to vary the design is mathematically defined in the form of parameters that tend to change in a permissible range. These parameters are called design variables and the notion of the limits on the design variables is called constraints. A typical optimization problem can be expressed as an objective function to minimization[3]

$$f(x) = f(x_1, x_2, x_3, x_4, \dots \dots \dots \dots x_n) \qquad \text{Objective (Eq1)}$$

Subjected to equality and inequality constraints

$$\left.\begin{aligned} h_i(x) &= 0\,;\, i = 1,2,3 \dots n \\ g_j(x) &= 0\,;\, j = 1,2,3 \dots n \end{aligned}\right\} \quad \text{Constraints(Eq2)}$$

Here, the vector x represents the design variables. If only Eq. (1) is minimized, the problem is called an unconstrained optimization problem. If Eq. (1) is minimized while ensuring that the design variables also satisfy the constraints in Eq. (2), the problem is called a constrained optimization problem. The values of the design variables obtained to form a design following the optimization process is called the optimal design.

Structural optimum design methods are evaluated based on design philosophy. The major part of the design studies weigh in the category of calculating safety factor value to judge the ultimate failure of the structure. The first requirement to be considered to satisfy optimization of any structure is to create a feasible solution. However, critical judgement must be valued to find the best of feasible designs. The best design can be measured using various factors like minimum cost, minimum weights, machinability of the optimal structure, solution being local optimum or global optimum. For metallic structures, in which the predictability of the failure is less complex, it follows two phase design optimization process. The first phase is topology optimization where an optimal layout of the design is formed within the available design space with respect to load conditions and in the second phase, the structures are sized and refined using size optimization[18,19,8].

2.2.1 Topology Optimization

According to M.P. Bendose[4], topology optimization is a phase where the layout of the structure is optimized within the available design space. In a typical topology optimization problem, the material distribution is performed in accordance with the design variables, constraints, and loading conditions. In 1988, Bendose, M.P. and Kikuchi, Noburu have proved that optimization method through topology with the material distribution method can provide optimal design[18]. Various studies have been done on topological optimization in the history and it is further described as the conceptual phase of design. Since manufacturing the exact designs can be a difficult task, these layouts can be standardized using different approximation methods[8].

2.2.2 Shape Optimization

Shape optimization has the primary objective to determine the optimal shape of the structure. Once the topology is decided, the shape optimization comes into place to design the shape of the structure while modifying the topological layout within the concept. This phase uses the outer boundary of the structure to modify the problem, various grid locations are allocated on the outer part of the structure to create an optimal outcome[5]. This thesis study does not directly use topology and shape optimization since the above-mentioned description suits best for the isotropic structures. Instead, this study uses the concept of free size optimization developed by Altair Optistruct to create designs for composite structures[6].

2.2.3 Size Optimization

While the conceptual designs are formed by topology and shape optimization, the size optimization deals with structural elements such as shell thickness, beam cross-sectional properties, spring stiffness, and mass are modified[7]. For isotropic metallic structures, the final design is obtained after this phase. Typically, it takes place after defining the layout and shape of the structure in the conceptual phase.

2.3 Composite Structural Optimization

The method of optimization for composite structures is highly variated from that of isotropic metallic structures like aluminum. The concept of creating an optimal design for composite materials started out in 1973 by Khot et al., an optimization method for fiber reinforced composites was introduced based on strain distribution method, where the minimum weight is found out through numerical search[8,9]. Further in 1976, the same problem was modified using stress and displacement constraints[8,10]. Starnes and Haftka investigated the weight problem of wing design using optimization method. The constraints used were panel buckling, strength, and displacement and the results were obtained on graphite epoxy material, boron spar caps, and all aluminum construction. Their study proved that composites are a far more favorable choice than aluminum mainly due to the freedom of changing the ply orientations than changing the total thickness[11,8]. Later the directional properties of composites were taken as an advantage of structural optimization, Triplett studied on the design improvements of F-15 fighter aircraft[12,8]. Schmit and Mehrinfar studied minimum weight designs of wing box structures with composite stiffened panel components while ensuring that failure modes such as panel and/or local buckling as well as excessive strain and displacement were not activated. The optimal design problem was broken into a system level design problem and a set of uncoupled component level problems. Results were obtained through a process of iterations between the system and component level problems. In later years, multilevel approaches to optimization became very popular in the design of aerospace composite structures[13]. Haftka and Walsh mentioned that practical applications limit the ply angles to 0, 90, and ±45 degrees and the laminate thickness to integer multiples of the ply thicknesses. The determination of the stacking sequence of the composite laminate therefore becomes an integer-programming problem or a nonlinear programming problem with integer or discrete design variables[14,8]. Graesser et al. considered the design problem for a laminated composite stiffened panel which was subjected to multiple bending moments and in-plane loads. The objective was to minimize structural weight while satisfying panel maximum strain and minimum strength requirements. The skin and stiffener ply orientation angles and stiffener geometry were considered as design variables. The authors also addressed the fact that ply angles may need to be limited to user specified values[15,8]. In 2014, Taylor R. et al., considered a laminate with a rectangular cut out with one hole with practical design constraints, studied, compared weights, and manufacturability through various optimization methods[1,42].

Orthotropic composite structures require higher level of tooling and additional processes in the conceptual level, design and manufacturing constraints at system level and stacking sequence optimization at the detail level to formulate the final design of the structure. Zhou, et.al[23] have developed such tools to execute a reliable optimization on orthotropic composite structures with three phases of optimization methods.

- First phase is a conceptual level optimization that determines the optimal ply shapes and location for maximum structural efficiency. This allows thickness distribution of element throughout the design space that meet the design requirements.
- Second phase is system level which determines the sizing for the ply bundles that has been shaped from the conceptual level. It is used to determine the thickness of each ply and furthermore the whole laminate with respect to the loading environment and manufacturing constraints.
- Third phase is detail level optimization where the stacking sequence of the plies in the composite laminates is determined in accordance with the design requirements.

2.3.1 Composite Free Size Optimization

This is a feature introduced by Altair OptiStruct to take the advantage of flexibility of thickness parameter in topological optimization of shell elements. In topological optimization, the thickness of the solid elements is best optimized but it is not precise while performing on shell elements. Free size optimization uses the thickness parameter as a size parameter and offers a direct fix for the precision problem in the shell elements. Thus, creating topological- style optimization result. However, this type is restricted to only isotropic materials, a generalized process can be used for the composite materials.

M.Pohlak et al.[16] have used free size optimization in a multi stage criteria optimization of large plastic composite parts.

The composite free size optimization presupposes the loading, composite structural and material data to create a design concept that creates most feasible design in accordance with the parameters involved. By varying the thickness of each ply per its orientation, the total laminate thickness is variated all along the design area along with the composition of composite structure at every point is simultaneously optimized. A super ply will be introduced, where all the optimized plies are arranged in accordance with the orientation. To neutralize the stacking sequence effects, SMEAR properties for the laminate stack is often used unless the user requires a specific stacking constraints to impose.

2.4 Structural and Manufacturing Criteria

To design a structure that withstands realistic loading environment, the requirements or criteria of design must cover structural as well as manufacturing aspects. The structural conditions are dealt within the purview of stability, stiffness, damage tolerance, etc. To ensure the design criteria to be implemented as constraints, appropriate tools and information in finite elemental methods are used. The manufacturing criteria is implemented to mainly avoid defects like interlaminar stresses, resin rich pockets, fiber, wrinkling, delamination, warpage, constructive stress interface, and complex shapes. This section discusses the structural, manufacturing, and design criteria and their purpose of implementation in this design problem.

2.4.1 Structural Criteria

As discussed above, the structural criteria include five major conditions i.e, strength, stability, bearing at bolted joint, stiffness and natural frequency. The static strength is based on classic laminate plate theory to determine point strains ply-by-ply and compare against laminate-based allowable ply strains developed from fiber-dominated laminate coupons in a building block test program[25]. Many commercial finite element codes support calculation of various ply-based composite failure theories, such as Tsai-Wu, Hill, or maximum strain, for prediction of static strength. In maximum strain theory, which is used in this work, no interaction is given between strain components. The ply failure index is calculated as the maximum ratio of ply strains to allowable strains as

$$F = \max\left(\left|\frac{\varepsilon_1}{\tilde{X}}\right|, \left|\frac{\varepsilon_2}{\tilde{Y}}\right|, \left|\frac{\gamma_{12}}{\tilde{S}}\right|\right) \qquad \text{eq (3)}$$

Where, $\tilde{X}$ - Allowable strain in ply material direction (1)

$\tilde{Y}$ - Allowable strain in ply material direction (2)

$\tilde{S}$- Allowable in-plane engineering shear strain

If different values of $\tilde{X}$ and $\tilde{Y}$ are provided for tension and compression, the appropriate values are used depending on the signs of ε_1 and ε_2 respectively. Structural stability is typically satisfied through finite element eigenvalue calculation. Damage tolerance is typically based on strain levels determined from compressive strength after impact testing for specific laminate designs and structural configurations[25]. Additional structural design criteria might include natural frequencies, as determined by finite element eigenvalue solution, or stiffness constraints, which can be applied using finite element displacement results.

Design of the composite laminate at bolted joints is of primary concern in composite structure. The behavior of a bolted joint in a composite material differs considerably from what occurs in metals. Hart-Smith and Niu[26,27] for example, discuss this behavior. In metal joints, load redistribution among fasteners due to local yielding produces failure at higher load levels than linear elastic analysis predicts. In composite materials, however, the relative brittleness of the material causes local stress peaks at fastener holes and negligible load redistribution. Additionally, bearing stresses generally interact with bypass stresses, which result from loads transmitted past the hole and result in reduced allowable bearing loads. Complex and often competing failure modes exhibited in composite bolted joints arise due to anisotropy and ply by ply lamination. Consequently, accurate failure prediction requires accurate characterization of the bearing and bypass stresses. Great effort has been focused throughout the aerospace industry to develop methods to achieve this accurate failure prediction. These methods range from purely empirical bearing-bypass interaction curve fits[28] to semi-empirical methodologies that calibrate analytical models to observed test results. These semi-empirical methods calibrate the stress state, such as in the Bolted Joint Stress Field Model (BJSFM)[29], or fracture mechanics solution, such as in the proprietary IBOLT tool[30].

2.4.2 Manufacturing and Design Criteria

Manufacturing and design criteria for practical laminate design include constraints for issues such as minimum gage limits, stacking constraints, and knowledge-based criteria for ply percentage limits and ply termination (i.e. ramp rate) and continuation restrictions. Incorporation of these constraints requires specific capabilities integrated within the finite element tool or a specific knowledge-based tool to drive the optimization. The current study investigates the ability of manufacturing constraints integrated in Altair OptiStruct to guide ply shaping optimization to manufactural designs. Ply drop constraints and ply shape complexity are investigated. Good laminate design practice limits ply drop-off rates to minimize interlaminar stresses and failure modes[31], constructive stress interference, delamination[32,33,34], micro-buckling under compression[35], resin-rich pockets, and fiber wrinkling[36]. Kassapoglou recommends the distance between successive ply drops be at least 10 to 15 times the dropped height[37]. Ply shape complexity directly influences producibility and cost. While manufacturing cost is difficult to quantify as a constraint in an optimization, indicators of ply manufacturability can be quantified using measures such as ply perimeter[36] or minimum ply (or tow) length and width[37]. This work examines minimum ply (or tow, if fiber placement is considered) dimensions as a metric for ply shape complexity and manufacturing cost.

3. DESIGN STUDY OF COMPOSITE LAMINATE

This section goes through the vital design study of this thesis, this is a continued study of the comparison study between three laminates. A constant thickness laminate, three zone laminate and optimal laminate are compared in terms of mass and buckling eigen values. In that study, constant thickness laminate was learned to have higher mass compared to other two variants. All models in this study are executed with the buckling constraints.

3.1 Objective

A design study has been executed to compare two different methodologies of optimization in terms of design weight and structural performance. Altair OptiStruct has been used to carry out the optimization process. A rectangular composite laminate with one hole in the center is optimized using two different methods.

- Three zone laminate
- Optimal zone plate

3.2 Threezone Laminate Design Vs Optimized Composite Laminate Design

The three-zone laminate is formed by using size optimization followed by shuffling optimization. Three basic ply shapes are assigned in the laminate. The shapes are created by engineering judgement. Each shape has increasing width to maintain a gradual slope except for the full ply.

a) Full- A ply shape that covers the whole design area

b) Bearing land – A ply shape that covers the area where the fastener loads are applied

c) Pad – A circular ply shape that acts like a padding around the central hole

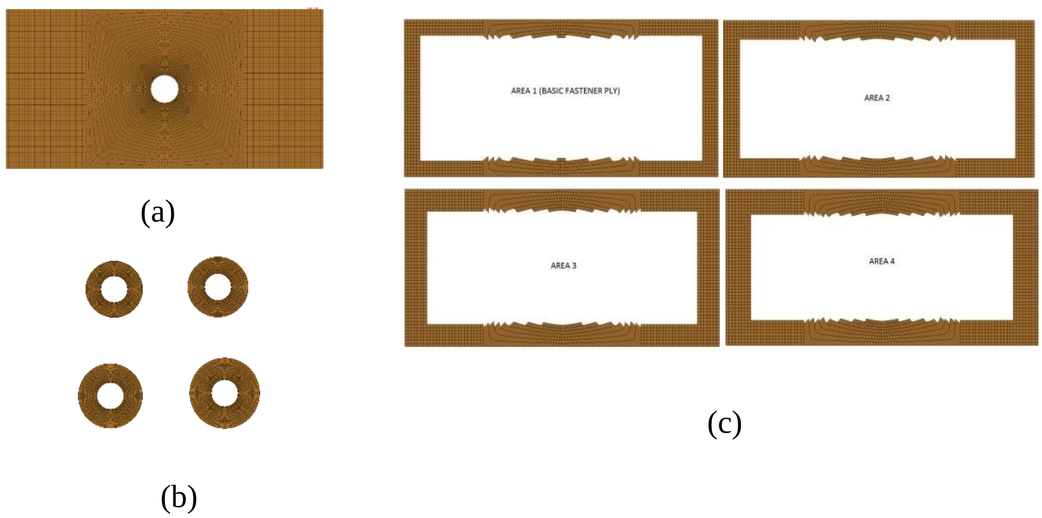


Figure 3: Three zone laminate – ply shapes
(a) Full ply
(b) Bearing land plies
(c) Pad ply

The optimal zone plate is created using three phase optimization method i.e, free – size optimization that creates ply shape in accordance to the constraints and loading conditions. In Altair Optistruct, number of plies to be generated for each orientation i.e, ply bundles can be controlled by the user. In this case, default ply bundle number is used (4 plies per orientation. After free size optimization, the laminate goes through size optimization that sizes and finalizes the thickness of each ply and gives out the mass of the whole laminate. This follows the shuffling optimization where the stacking sequence is decided.

A fastener land ply is included in the laminate before the size optimization in the laminate to ensure smooth distribution of material and to increase manufacturability of all the plies. The shapes of all the plies that are formed around the fastener locations are omitted to regulate the overall thickness of the elements. After successfully shaping the plies and adding the required conditions to the finite elemental model, size optimization is executed.

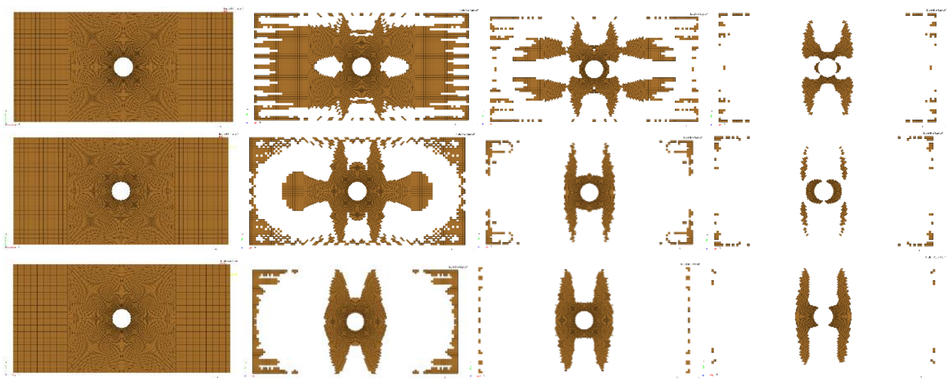


Figure 4: Ply shapes after free-size optimization

3.3 Model Formulation

This section specifies the details of the models that includes geometry, loads, material, structural criteria, and manufacturing criteria.

3.3.1 Geometry with load conditions

The dimensions of the laminate are 10 inches by 20 inches with unidirectional fibers on plies of $[0^0/\pm 45^0/90^0]$ family that has a centrally located hole of 1.75-inch diameter as shown in figure.

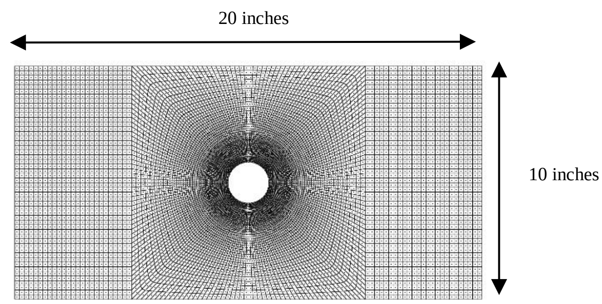


Figure 5: Laminate dimensions

Compression, tension, and shear loads are applied as distributed point loads along the fastener locations, that are spaced with 0.25 inch fasteners at 5d pitch. As shown in the figure 6 (a), (b), (c), the magnitude of compression and tension loads are 20,000 $^{lb}/_{in^2}$ (20 kips on short edge) and magnitude of 10,000 $^{lb}/_{in^2}$ for shear load with 20 kips on long edge and 10 kips on short edge.

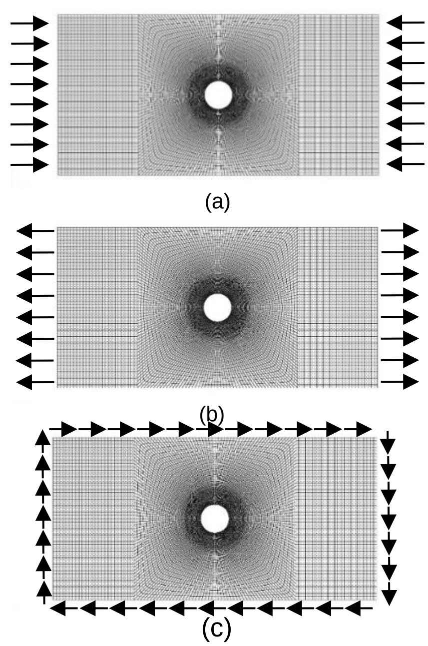


Figure 6: loads on the laminate (a) Compression loads (b) Tension loads (c) Shear loads

3.3.2 Material

The material used is a unidirectional carbon fiber/epoxy tape with the properties shown in table. A 'MAT8' orthotropic material in Altair Optistruct is used as material property on the laminate.

Property	*Value*
E_1	20,000,000 psi
E_2	1,000,000 psi
G_{12}	800,000 psi
G_{23}	500,000 psi
ν_{12}	0.30
t_{ply}	0.01 in
ρ	0.06 $^{lb}/_{in^3}$

Table 1 : Generic composite material properties

3.3.3 Acreage Strength Criteria

The final objective of this optimization is to minimize the mass of the laminate. The structural criteria mentioned above are assigned as constraints. Static strength and damage tolerance are constrained using strain limits in max strain failure condition and are mentioned in the table.

Allowable	*Value*
X_T	$2.5 \times 10^{-3}\ ^{in}/_{in}$
X_c	$2.5 \times 10^{-3}\ ^{in}/_{in}$
Y_T	$0.2 \times 10^{-3}\ ^{in}/_{in}$
Y_c	$0.4 \times 10^{-3}\ ^{in}/_{in}$
S	$0.4 \times 10^{-3}\ ^{in}/_{in}$

Table 2: Generic carbon fiber/epoxy tape material system maximum strain criterion allowables

3.3.4 Bearing – Bypass Criteria

The Bearing load is a load that is reacted at a fastener hole and bypass load is a load that escapes the fastener hole without any interaction. The bearing and bypass constraints are enforced at fastener locations. These constraints are defined at two end points at fastener locations that captures peak loads which covers fastener locations. Additional tailoring of the bearing land region by adding more locations. To calculate margin of safety, bearing and bypass loads are enforced in this location. The bearing stresses are calculated based on Jean Claude Fiabel's study[44] on practical stress analysis for design engineers, from the component forces along 1 and 2 directions, they can be represented as

$$Bearing\ stress_1 = \frac{f_{1xs}}{2(t_0+t_{45}+t_{-45}+t_{90})\times d} \qquad \text{eq (4)}$$

$$Bearing\ stress_2 = \frac{\sqrt{(f_{2xt}-f_{2xc})^2+(f_{2ys})^2}}{2(t_0+t_{45}+t_{-45}+t_{90})\times d} \qquad \text{eq (5)}$$

Where, $f_{1xs}, f_{2xt}, f_{2xc}, f_{2ys}$ are calculated from the allowables mentioned in table, d is the diameter of the fastener hole allocated and $t_0,\ t_{-45},\ t_{45},\ t_{90}$ are the thickness of total number of plies of the orientations 0^0, 45^0, -45^0, 90^0 respectively. The constraint curves are applied as a series of equations to define the allowable envelope described by Grant and Sawicki as shown in Figure 9. Actual application of the interaction curves requires a complete test program as outlined by Grant and Sawicki[28]. Arbitrary values are applied for the generic material system in this work.

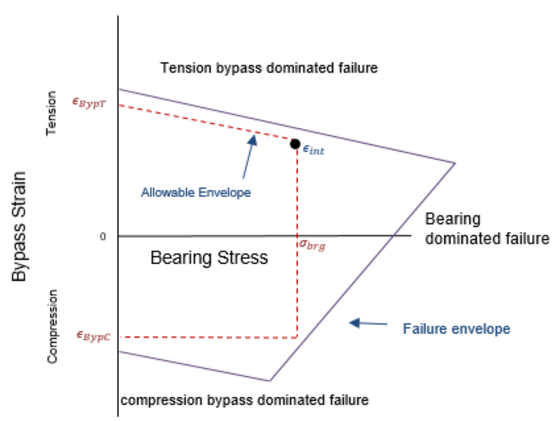


Figure 7: Bearing – bypass interaction curves adapted from Grant and Sawicki[28]

Constant value allowables for compressive bypass strain, ϵ_{BypC}, and bearing cutoff stress, F_{Brg}, used to define the constraint envelope are given in Table 3 below. ϵ_{BypC} and F_{Brg} are applied directly as constraints in the bearing land region of the optimization. The linear interaction between tensile bypass strain and bearing cutoff stress is determined using two equations. First, the tensile pure bypass strain allowable, ϵ_{BypT}, for the generic composite material system is calculated as a function of the difference between the percentage of 45º angle plies and loaded 0º plies (also known as AML or Angle Minus Loaded) is calculated the graph shown below.

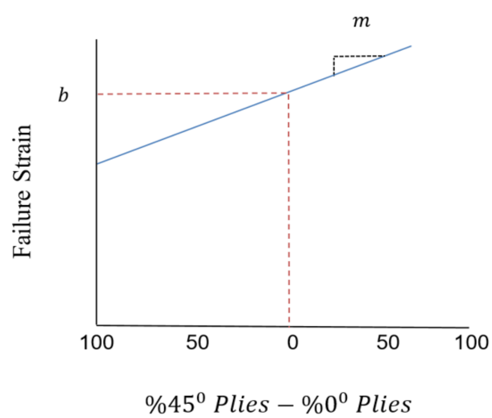


Figure 8: Tensile failure strain vs AML adapted from Grant and Sawicki[28]

And the value of tensile bypass strain can be written as

$$\epsilon_{BypT} = (per45^0 - per0^0)m + b \qquad \text{eq (6)}$$

Where $Per45^0$ and $Per0^0$ are the local ply angle percentages and the slope, *m*, and intercept, *b*, are material-specific values arbitrarily determined for the generic composite material. This relationship is shown in Figure 7.

Next, the linear interaction limit strain, ϵ_{lim}, is calculated as

$$\epsilon_{lim} = \left(\frac{\epsilon_{int} - \epsilon_{BypT}}{F_{Brg}}\right) . \sigma_{brg} + \epsilon_{BypT} \qquad \text{eq (7)}$$

Where σ_{brg} is the local bearing stress and the linear interaction strain, ϵ_{int}, is material-specific and are arbitrarily determined for the generic composite material. The values used for ϵ_{int} is shown in Table below. ϵ_{lim} is shown as the upper allowable boundary in Figure 2 and is the tensile constraint used in the bearing land region in the optimization.

Allowable	Value
Compressive Bypass Strain, ϵ_{bypC}	$4.2\times10^{-3}\ {in}/{in}$
Bearing Cutoff stress, F_{Brg}	$80\ ksi$
Linear Interaction Strain, ϵ_{int}	$2.9\times10^{-3}\ {in}/{in}$

Table 3: Generic carbon fiber/epoxy tape material system constant value bearing and bypass allowables

3.3.5 Buckling Criteria

Static structural stability is constrained through a lower limit on buckling eigenvalue during sizing optimization. For weight-efficient buckling resistance, ply shapes must be able to develop thickness in appropriate regions of the plate to resist the transverse displacement of the buckling waves. The previous study showed that composite free size optimization did not directly generate buckling resistant ply shapes when only in-plane loading is applied[1,42]. Because a buckling constraint is not compatible with the minimum compliance objective, a tedious process of separate free-size optimization for each load case would be required. Consequently, a procedure to generate ply shapes more resistant to out-of-plane deflections, and therefore more buckling resistant, has been applied wherein a surrogate pressure load is used. Since the load is fictitious, magnitude is uncertain, with higher values driving greater intensity of material concentration. The ply shape trends that are formed by using pressure values of 0, 0.5, 1.0, 2.0 and 3.0 in free size optimization are studied. Since composite free size thickness results are developed on relative stiffness basis, the absolute sizing of the laminate is not determined until sizing optimization. In sizing optimization, the buckling eigenvalue is constrained to be greater than 1.02 for the compression and shear load cases. In all design models, the shear buckling eigenvalue was very large and therefore not active in the optimization. Consequently, only compression buckling results are shown.

3.3.6 Design Criteria

Constraints are applied to enforce composite design rules of thumb and to ensure a producible laminate. In free size optimization, total slope of the laminate is induced as a constraint and the total drop constraint is implemented in size optimization. The manufacturing constraints are applied as follows

- 0º and 90º ply percentages within 20%-60% of the total laminate stack at all locations
- Balanced 45º and -45º plies at all locations
- Symmetric laminate stack
- Single ply thickness 0.005-inch-thick—ply counts based on this thickness
- The laminate thickness is set to a minimum limit of 0.010 inch

3.3.7 Manufacturing Criteria

Two manufacturing criteria are applied as constraints:

- Ply ramp rate and Ply drop off rate
- Minimum tow dimensions on plies

In the OptiStruct three phase optimization process, ply drop constraints can be implemented using several options in free size optimization and sizing optimization based on either slope or thickness drop applied to either the total laminate or at the ply level[40].

This work uses an element-to-element slope constraint on the total laminate (TOTSLP) during free size optimization and a maximum thickness drop constraint applied to the total laminate (TOTDRP) during sizing optimization.

For free-size optimization, the effect of ply drop rate on ply shape is studied by developing ply shapes at three settings of the total slope (TOTSLP) control: none, 0.10 (10:1 ramp), and 0.05 (20:1 ramp). For size optimization, the total drop (TOTDRP) control sets the total laminate thickness change at any ply/zone boundary. This control can be idealized in different ways depending on geometry and how many ply shapes are developed for each ply angle. If panel geometry is large relative to ply shapes, the geometric significance of the ply drop regions on the overall design is minimal (see for example Henson, et al.[41]) and the maximum drop can be applied directly, as shown in Figure 9 (a), where the shaded triangle represents the ply drop ramp that is not modeled. If, however, the panel is small relative to the ply shapes, the ramp geometry is non-trivial to the overall panel design and may need to be explicitly modeled. The relatively small panel dimensions in this work fall under this second case so additional ply shapes have been generated to allow explicit ply steps to be shown, as in fig 9 (b).

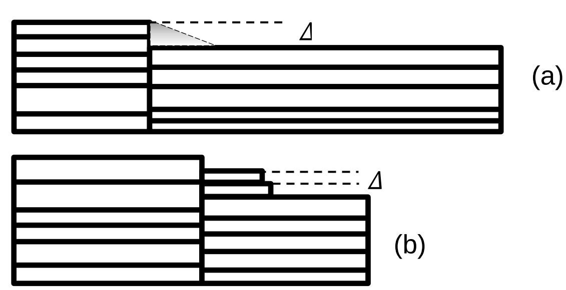


Figure 9: (a) Ply drop and slope effect on larger panel (b) Ply drop effect on smaller panel (plies added explicitly)

For this work, minimum tow length and width constraints are applied to guide ply shape manufacturability. Minimum tow length and width magnitude rules are applied as outlined in section 3.5 along the fiber direction of the respective ply in the laminate to edit the element sets that form the ply shapes. Arbitrary values are set based on the panel size and complexity used in this work. Larger minimum dimensions would likely be required for many fiber placement machines.

3.4 Free Size Optimization

The final plate optimization also uses ply sizing optimization but first adds a preliminary conceptual phase to determine optimal ply shapes based on the loading environment. Whereas ply sizing optimization seeks to minimize weight against quantified structural and design criteria, the free size optimization used in this phase, like topology optimization used for isotropic metallic components, seeks load path efficiency.

Free-size optimization generates 4 shapes for each ply angle for a total of 16 plies for each of the 9 design models. +45º ply shapes are identical to -45º ply shapes due to the balance constraint so only one set of plies is shown for ±45º ply bundles. The 4 bearing land plies, shown in Figure 4, with stepped widths were also added to each design model for a total of 20 plies per model. A Tcl script was developed add these plies automatically to each model. Since the bearing land plies are identical for each design model, they are not shown again. Unedited ply bundles are shown in Figure0.

Many of the ply shapes developed display geometric complexity, such as thin features and small holes or gaps, which would drive manufacturing cost and schedule beyond acceptable limits. Consequently, the ply rules outlined in section 3.4.2 are applied to reduce ply complexity based on producibility constraints. Ply bundles edited based on these rules are shown for 0º plies in Figure 16, for ±45º plies in Figure 17, and for 90º plies in Figure 18. Geometric complexity is greatly reduced yet the basic material distribution remains evident in most plies. Note that some ply shapes still exhibit rough edges due to mesh discretization patterns. Smooth ply shapes would be developed for actual manufacture of a design.

3.4.1 Parameters

The objective function in this phase is to minimize compliance (maximize stiffness) of the plate. A volume fraction constraint forces material distribution in the most efficient locations to shape ply bundles. The previous study determined ply shapes using a 40% volume fraction constraint yielded a lighter weight design[1,42] so this value was again used. As discussed previously, a surrogate pressure load is used to develop buckling resistant ply shapes during the composite free size optimization. Ply shapes are developed for pressure magnitudes of 0.0, 0.5,1.0, 2.0, 4.0 and 6.0 psi and Total slope ply drop constraint values of none, 0.10, and 0.05. The resulting thickness plots are shown in Figure 15 below. As the pressure load is increased, a thickened region forms to stiffen the plate against out-of-plane deflection. As the ply drop rate is reduced, the thickened region spreads to reduce the intensity of material build-up.

3.4.2 Ply shaping Rules

1. Holes or gaps along the fiber direction
    - If hole or gap is less than 100% of tow length requirement, then elements are added to fill area
2. Tow dimensions along the fiber direction—0º and 90º plies
    - Must be greater than 2" (fiber direction) x 0.50" (transverse direction)
    - If tow dimension is less than 50% of tow length/width requirement, then elements within area are removed

- If tow dimension is greater than 50% of tow length/width requirement, then elements within area are added until minimum dimension requirement is satisfied

3. Tow dimensions along the fiber direction—±45º plies

- Must be greater than 2” x 2” to ensure balance constraint enforced
- If tow dimension is less than 50% of tow length/width requirement, then elements within area are removed
- If tow dimension is greater than 50% of tow length/width requirement, then elements within area are added until minimum dimension requirement is satisfied.

The manual application of the rules requires detailed observation of each tow length and width along the fiber direction of the ply[42]. It is best described by showing the application. The following model was obtained with pressure of 3 psi with total slope constraint of 0.05.

Since the full plies and fastener plies prequalify the minimum tow dimensions, only 9 plies are required to be modified. All the plies must except the full plies are required to be subtracted from the bolted joint region or bearing land region as shown in figure 11. These plies are edited in accordance to the above-mentioned rules. In figure 12, 13, and 14. The blue rectangles are represented to specify that the particular region needs more elements while the red rectangles specify that the elements in that region needs to be removed. In the case of $\pm 45^0$ ply edits, the plies are translated to horizontal axis for the user convenience.

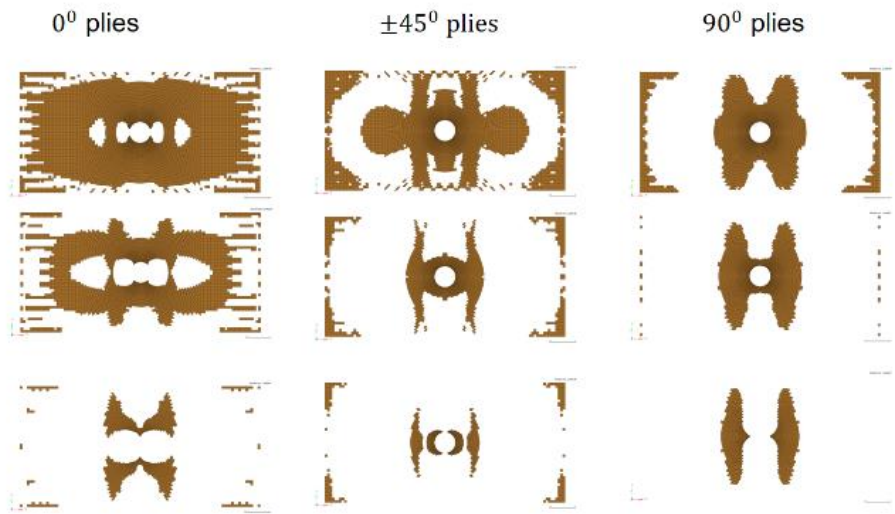


Figure 10: Ply shapes obtained from free size optimization

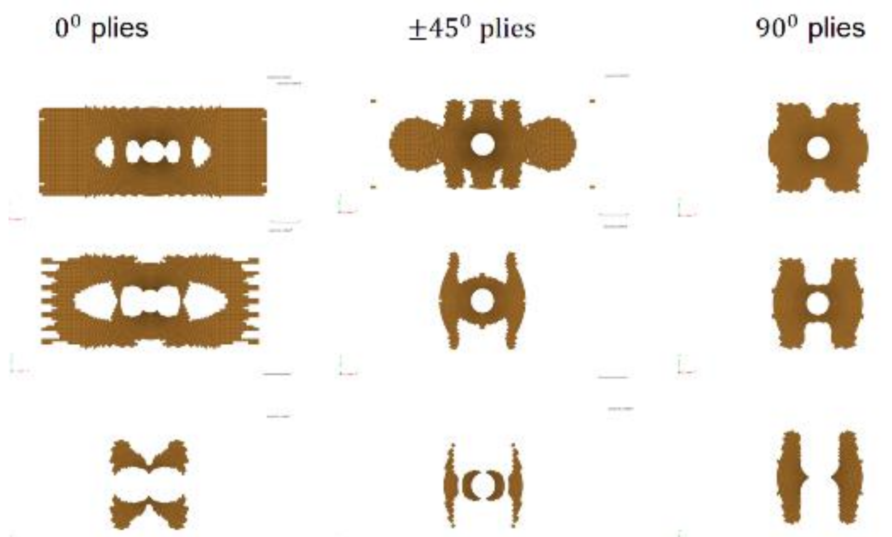


Figure 11: Ply shapes after the subtraction of bearing land region

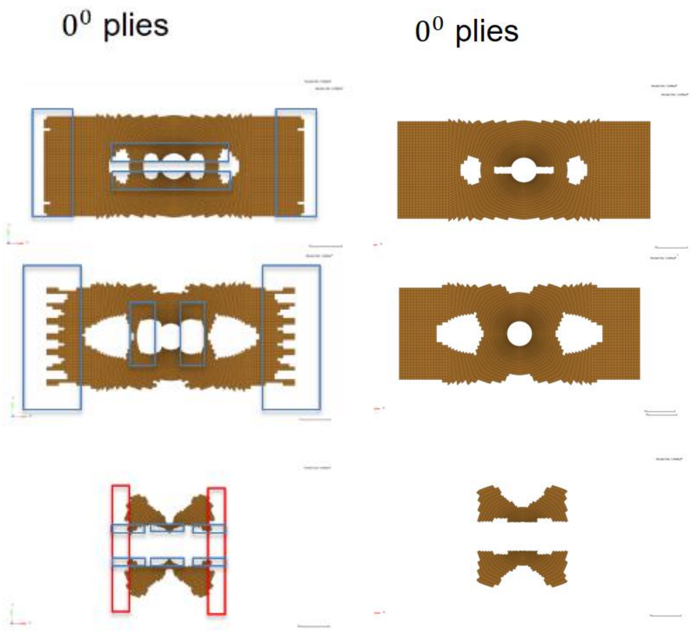


Figure 12: Unedited and edited Ply shapes of 0^0 fiber orientations

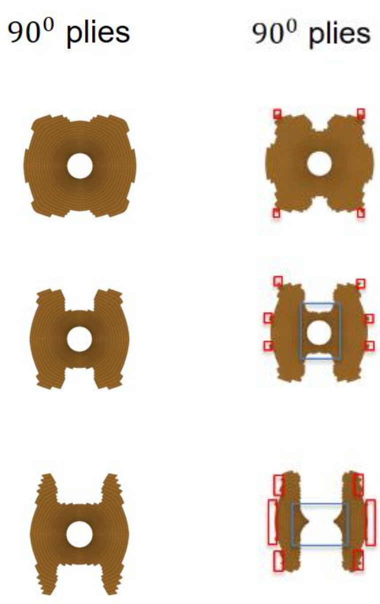


Figure 13: Unedited and Edited Ply shapes of 90^0 ply orientations

$\pm 45^0$ plies

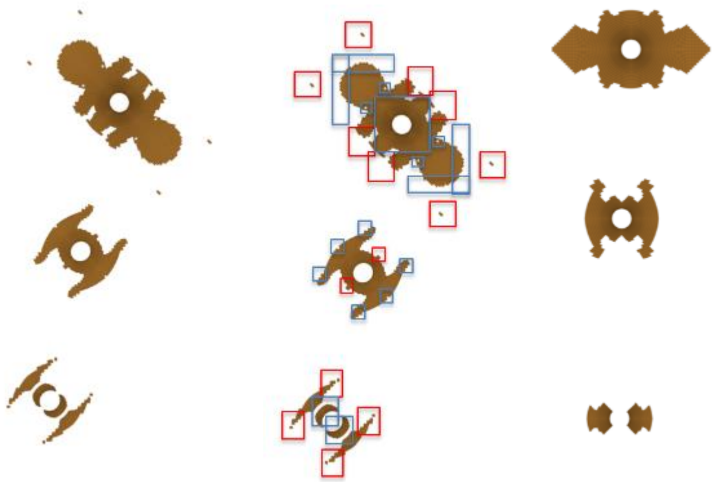


Figure 14: Ply shapes of $\pm 45^0$ orientations

The lengths and widths are checked and verified that they qualify the minimum tow dimensions. Since the some of the red lines are in the pad area, the area must be filled with a minimal tow dimensions and the irregularities are smoothened along the fiber directions. The red lines on the corners of the ply are filled with elements until it reaches to the minimum tow length since the length is more than 50% of the required tow length. The result would look as shown below. After plotting the boundaries, the elements near the hole are marked and ends of the midsurface region of the ply are marked with red and the other regions are marked with blue. After editing the ply, all the irregularities in the ply are smoothened along the fiber direction.

3.4.3 Ply shape results

The following table shows the ply shape results of 0^0 , $\pm 45^0$, before being edited and after being edited by following the ply dimensional constraints.

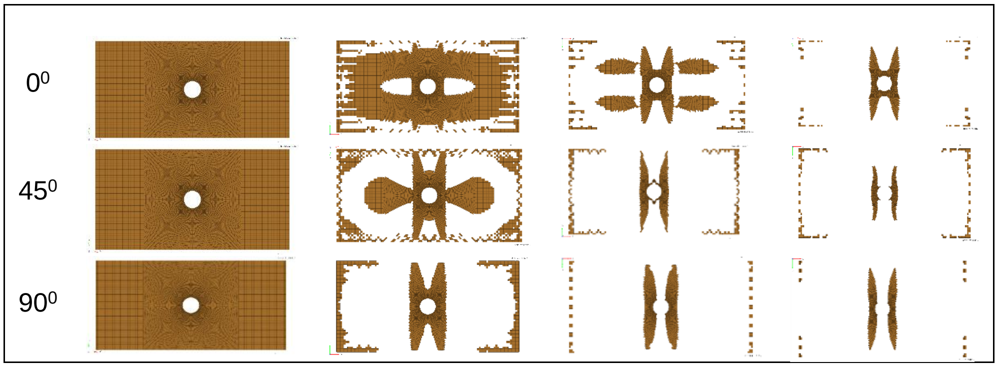


Table 4: Unedited ply shapes from pressure – 3 psi, No total slope

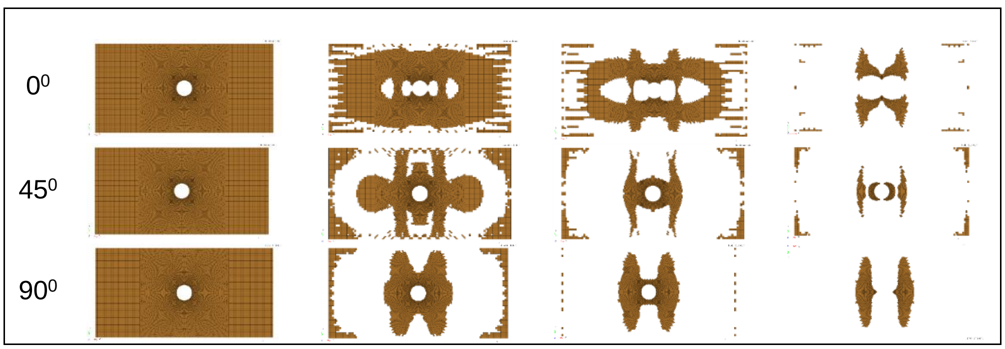


Table 5: Unedited ply shapes from pressure – 3 psi, Total slope – 0.05

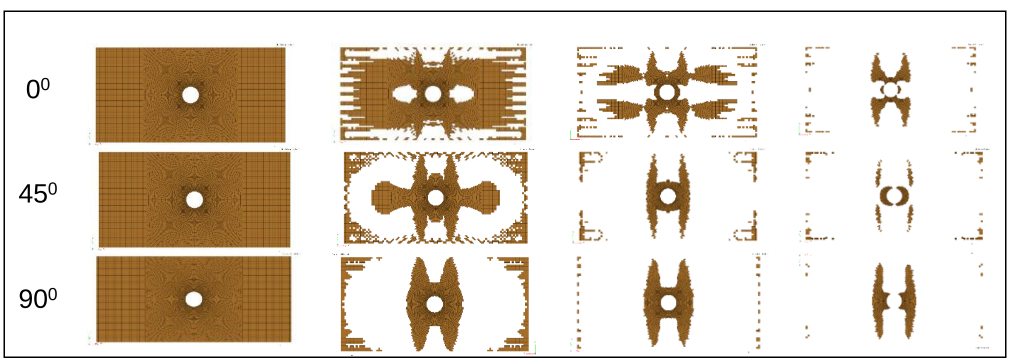


Table 6: Unedited ply shapes from pressure – 3 psi, Total slope – 0.1

After applying the rules mentioned in section 3.4.2, the above shapes are formed as shown in table 7,8 and 9. It is evident from the edited plies that the shapes are less complex and manufactural because of excessive material removal and smoother edges along the fiber direction.

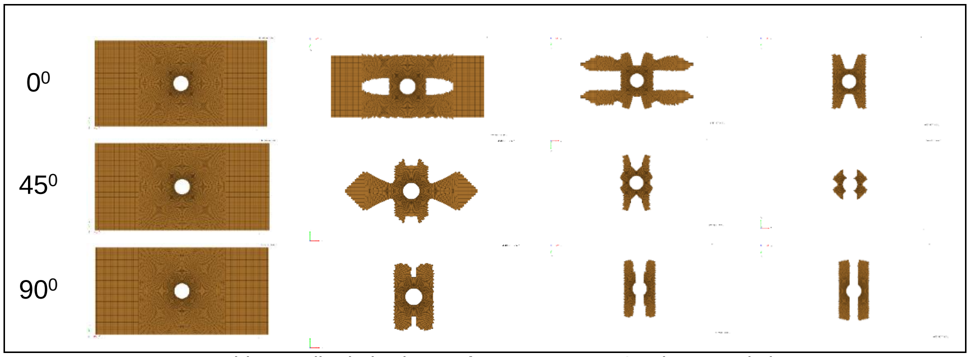


Table 7: Edited ply shapes from pressure – 3 psi, No total slope

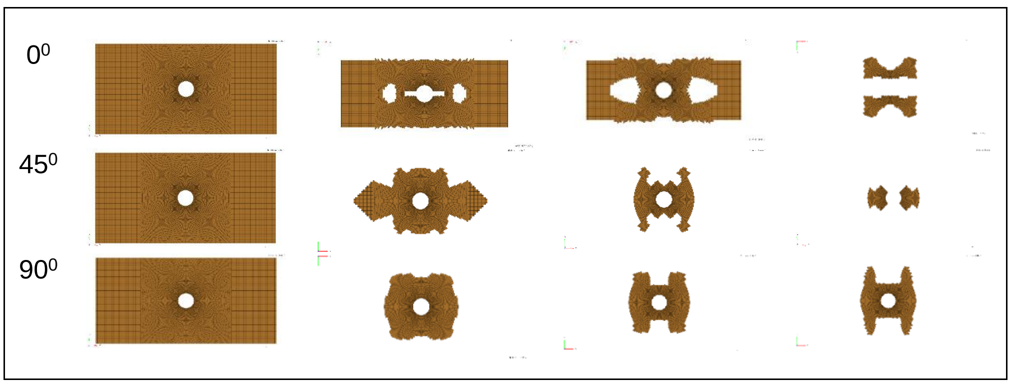


Table 8: Edited ply shapes from pressure – 3 psi, Total slope – 0.05

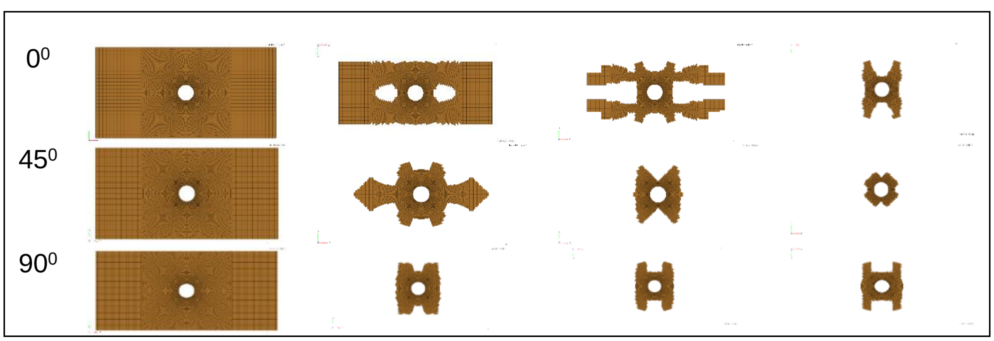


Table 9: Edited ply shapes from pressure – 3 psi, Total slope – 0.1

3.5 Size Optimization

This section showcases the set-up parameters and regulations required for size optimization.

3.5.1 Parameters

Since, free size optimization phase had an objective definition to create buckling resistant shapes while using 40% of volume fraction, the requirements to size a composite structure varies according to the final objective intended. The final objective of this phase to achieve a design is to minimize weight. The above-mentioned design and manufacturing constraints are implemented using responses and dequations. The maximum failure strain theory with maximum and minimum strain limits is applied as a constraint along with marginal strain values on two peak locations. Additionally, a lower limit of 1.02 eigen value is applied as buckling constraint along with the incorporation of bearing stress on the model.

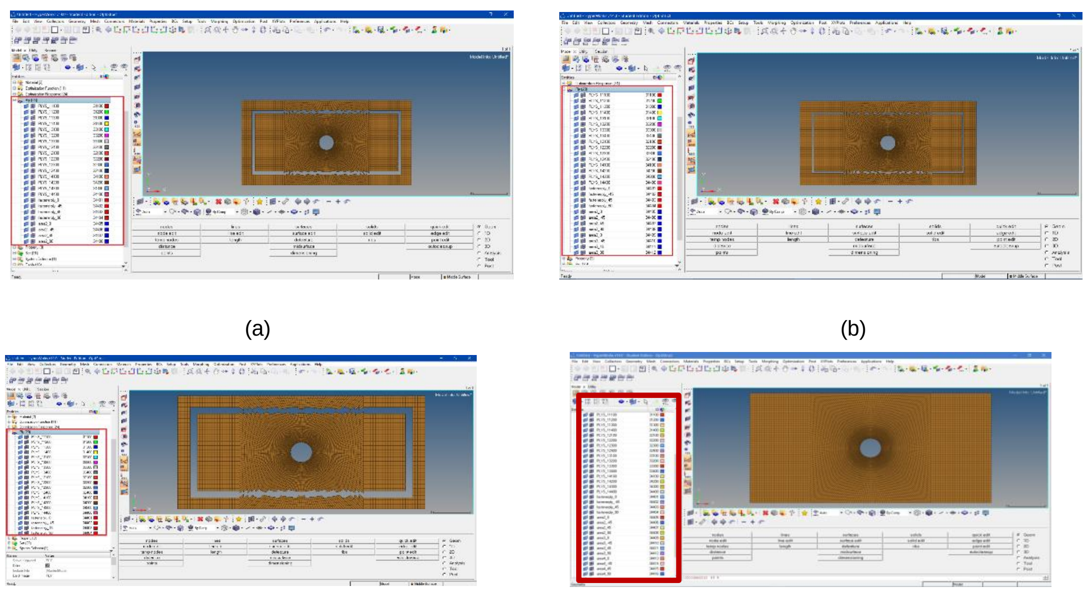
After free size optimization, four additional plies are added per orientation to withstand the loads in the bearing land region. Additional design variables and the relationships of them with the respective fastener plies are added. A global search option is used in this study for size optimization to avoid local optimization results.

3.5.2 Automated Regulation for size optimization

Due to addition of various plies and constraints after free size optimization, a time-taking manual addition of these features are required. A Tcl script has been developed to automate the functions required to proceed further for size optimization. It performs following functions such as creation of fastener plies, changing output card from fstosz to sztosh, enables DGLOBAL card, changes objective function, adds design variables, and respective design variable relationships with the plies and sets the limit of design variables

This Tcl script has been generated using if-else statements, the conditions were extracted from the command file and a macro file is created to generate a button in the user page. After running the script, a getstring function will be called to get a user input to enter number of required fastener plies. An input from the user is required to enter the number of ply bundles per orientation.

A button was created using "*createbutton" command in macro file named "userpage.mac". This file creates the required button in the user page in the utility menu in the GUI of Hyperworks. The Minimum value of the input is 1 and the maximum value that user can enter is 4. If the input number exceeds the limit, an error message will appear in the bottom left corner of the Hyperworks window. The variation of results for each input is shown below in figure 15.



(a) (b) (c) (d)

Figure 15: Tcl code application (a) with input 1 (b) with Input 2 (c) with input 3 (d) with input 4

3.5.3 Mesh Quality

Mesh quality in this study is checked on the basis on stress concentration factor, according to M. Acin[42], the stress concentration factor K_t defines the mesh quality,

if $K_t > 3$, over refined mesh

$K_t < 3$, coarse mesh

$K_t \approx 3$, accurate mesh for finite plate ($K_t = 3$, for infinite plate)

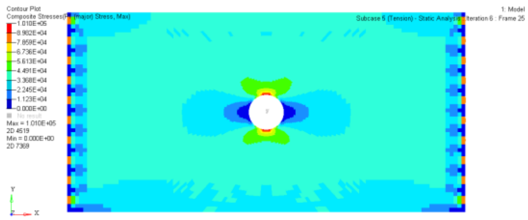
Considering the tension load case, the stress concentration factor is calculated from figure 17. The maximum stress value at the hole which is located on the top left corner of figure 17 which is the quarter part of the model. Principal major stresses were plotted on the laminate. Stress from an element which is far away from the hole has been selected to calculate K_t shown in Equation 8. The principal major stresses on the laminate for different subcases are shown in figure 16.

$$K_t = \frac{\sigma_{max}}{\sigma} \qquad \text{(Eq8)}$$

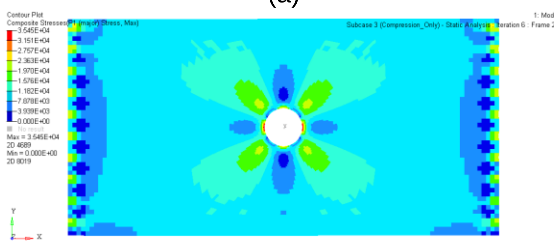
σ_{max} = Maximum Stress near the central hole = 10.10×10^4 psi

σ = Stress on the element away from the hole = 3.44×10^4 psi

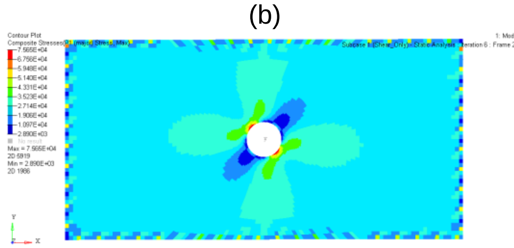
K_t = 3.005 ≈ 3.00, therefore the mesh obtained is accurate



(a)



(b)



(c)

Figure 16: Principal major stresses on different load subcases
(a) Tension loadcase
(b) Compression loadcase
(c) Shear Loadcase

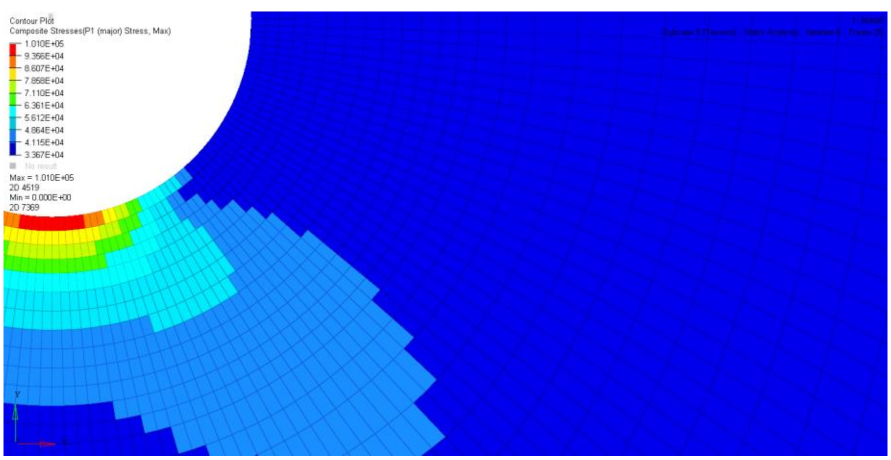


Figure 17: Stress peak at the hole for tension loadcase

4. RESULTS AND COMPARISONS

The size-optimized minimum weight designs accounted for strength (including damage tolerance strain allowable and fastener bearing bypass), stiffness, buckling stability, and manufacturing ply drop and tow length criteria. Section 4.4 shows optimized weight results for each design case studied. These results show no observable trend for the values studied. Furthermore, differences in weight values lie within the noise range of the modeling idealization and assumptions for the plate with the largest values less than 5.3% greater than the smallest. Consequently, no observation can be made about weight improvement or sensitivity to the method and parameters studied. It is believed that this lack of trend can be partially attributed to the laminate overdesign discussed in the previous section.

4.1 Free size Optimization Results

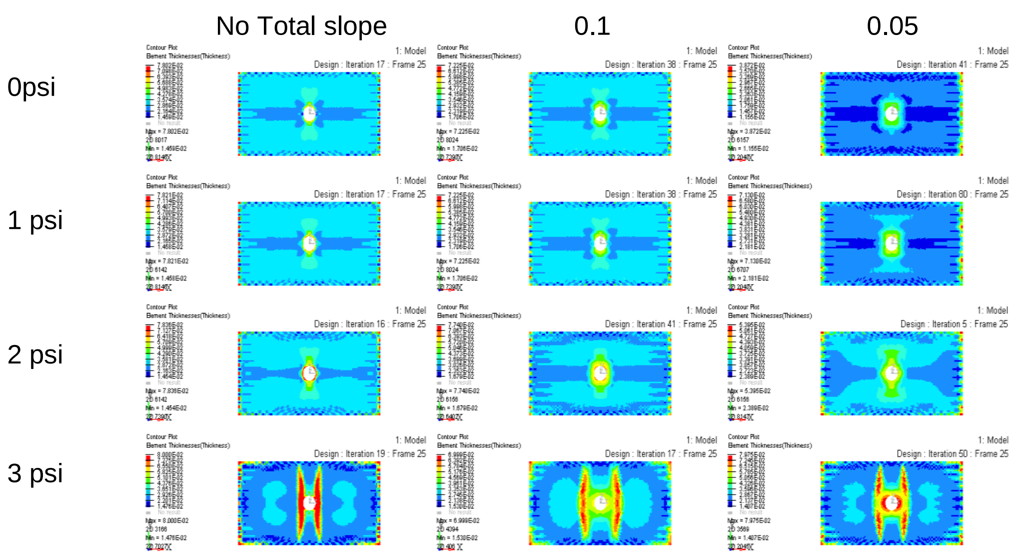


Figure 18: Free size optimization results

Free size optimization results are evaluated in 12 different cases with combinations of 0 psi, 1 psi, 2 psi, 3 psi along with ply drop off constraint with no total slope, 0.1 total slope, 0,05 total slope values. From figure 17, As the increase in the pressure, the material concentration on the midsurface is increased to create a buckling resistant shape for out of plane loading. As far total slope value decreases, the thickened region spreads to reduce material intensity.

4.2 Size Optimization Results

The results shown below in figure 18,23,28 are the final element thickness distribution of the three different cases extracted from free size optimization. 12 values of total drop are investigated to study the total drop trend. The mass comparisons of all the results are shown in section 4.4. Strain levels are typically very low for all the model variants and are shown in figures 19, 20, 21 and, 22 for case 1, figures 24,25,26,27 for case 2, figures 29,30,31,32.

Following determination of optimal ply shaping during the conceptual phase, sizing optimization determines thicknesses of the resulting ply bundles to meet the defined structural criteria. OptiStruct automates many aspects of creating the sizing optimization model based on the free size optimization model. Nevertheless, many details must still be specified for each of the models run in this study. Discrete optimization was executed based on the manufacturable ply thickness and the previously discussed manufacturing constraints for ply percentage, balance, symmetry, and ply drop rate were enforced. The objective of the optimization during this phase was minimum weight and the previously discussed structural constraints for max strain, bearing/bypass, and buckling were applied. The surrogate pressure load used to develop buckling resistant ply shapes is discarded for the size optimization and only the 4 design load cases are applied. The total drop (TOTDRP) constraints are applied for twelve values: none, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, and 0.2. The resulting laminates have variable thickness across the component due to the ply drops at the boundaries of the ply bundles. The effects of pressure and ply drop rate are again evident in the definition and material concentration intensity across the middle of the plate. Plots of the max strain failure index at the final size-optimized design for the three load conditions indicate regions of peak strain around the hole and at fastener locations. The buckling mode shape exhibited the same double half-wave pattern seen in the three-zone plate. These failure criteria and buckling plots results are typical for all design cases—only specific magnitudes are different. The optimization iteration histories show that the buckling constraint drives the sizing. Buckling eigenvalues ranged from 1.022 to 1.327 across the design models studied. These values are well above the 1.02 constraint imposed in the optimization setup as shown in figure 39. This discrepancy is believed to be due to discreteness of design options and limited design freedom that drives laminate overdesign with respect to buckling constraint.

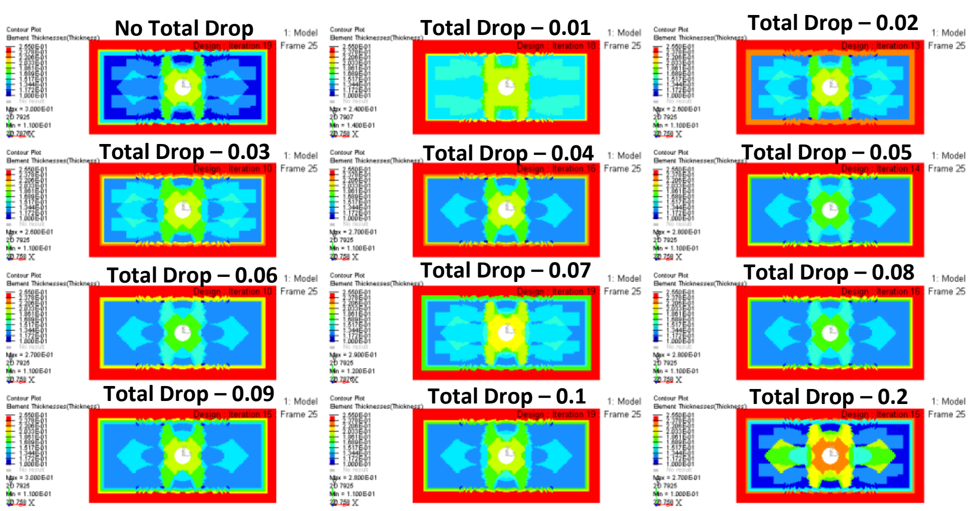


Figure 19: Size optimization results from the case – Pressure 3 psi, Total slope 0

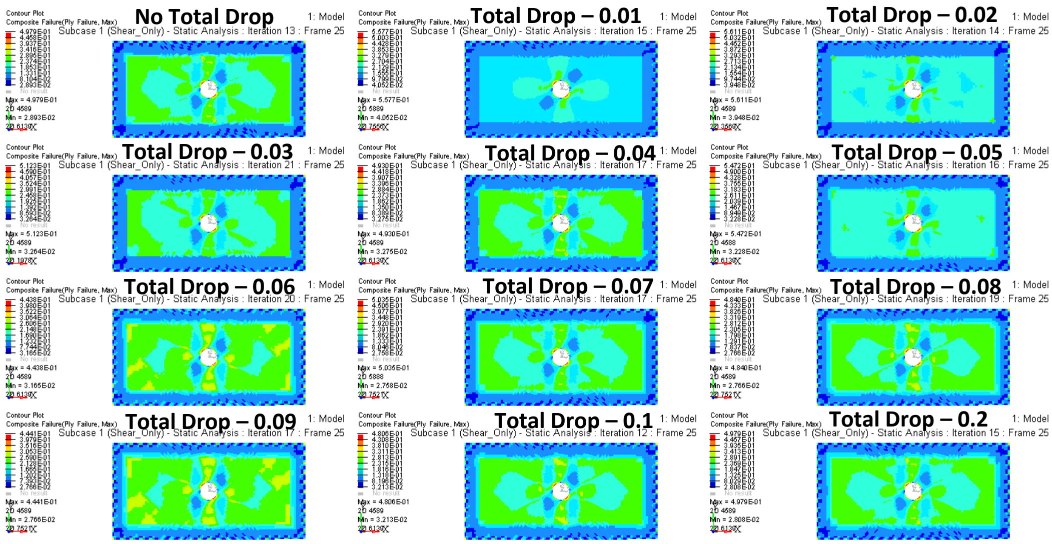


Figure 20: Failure criterion modes for shear loading from the case – Pressure 3 psi, Total slope 0

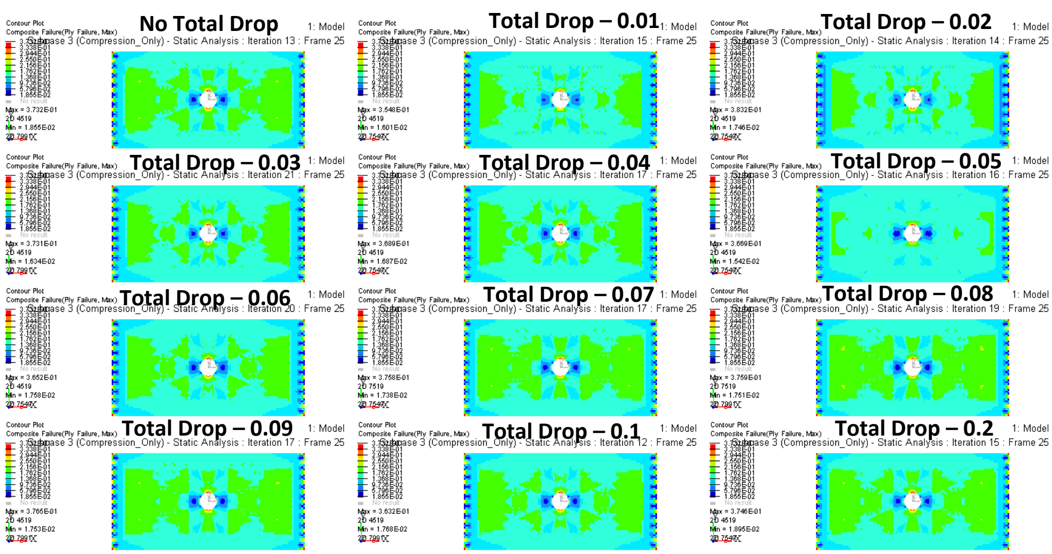


Figure 21: Failure criterion modes for compression loading from the case – Pressure 3 psi, Total slope 0

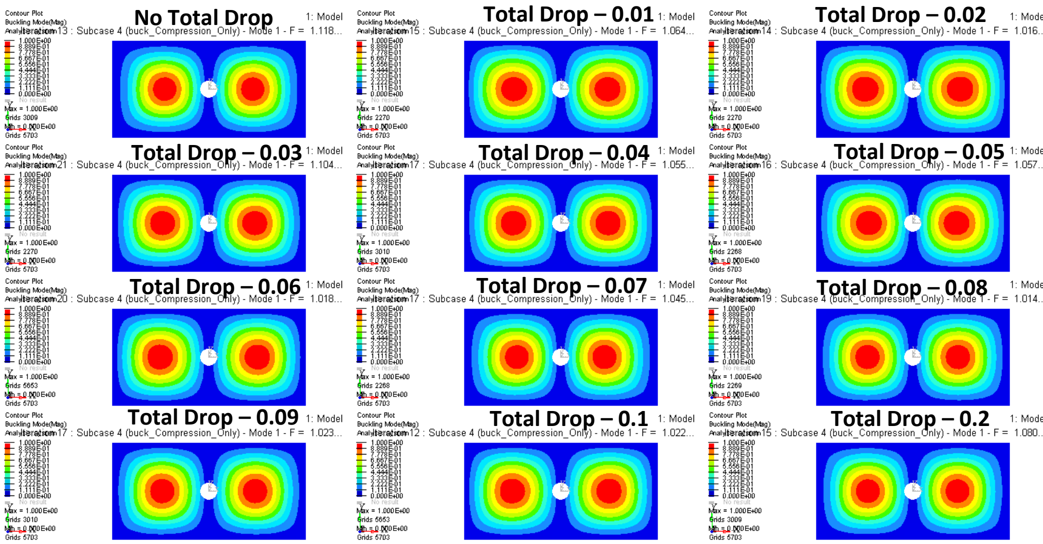


Figure 22: compression buckling loading from the case – Pressure 3 psi, Total slope 0

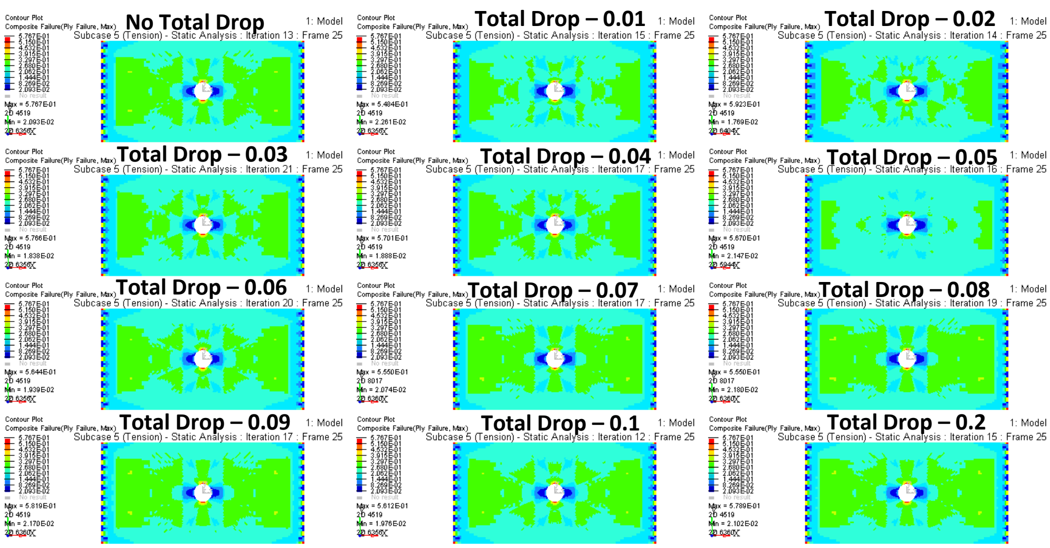


Figure 23: Failure criterion modes for tension loading from the case – Pressure 3 psi, Total slope 0

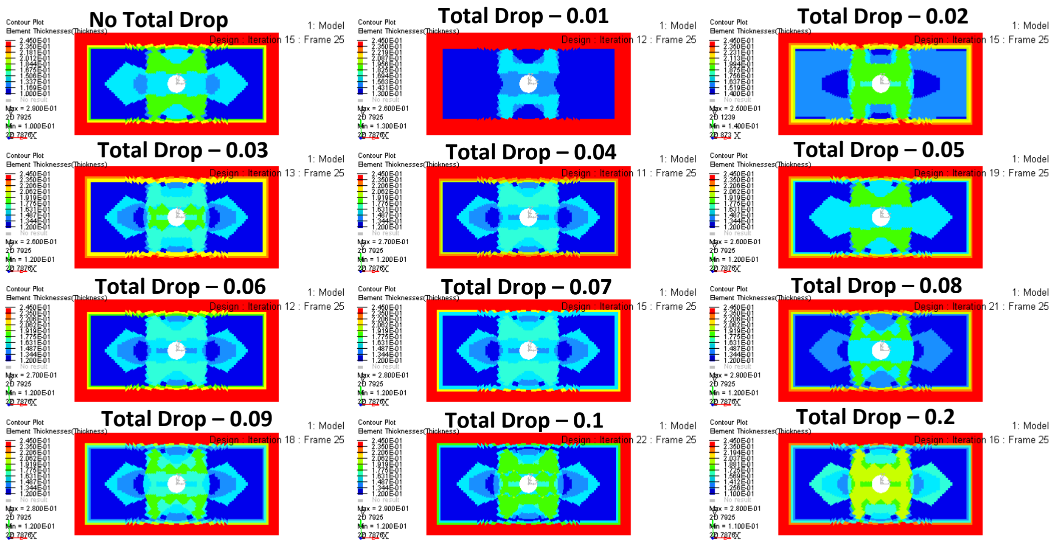


Figure 24: Size optimization results from the case – Pressure 3 psi, Total slope 0.05

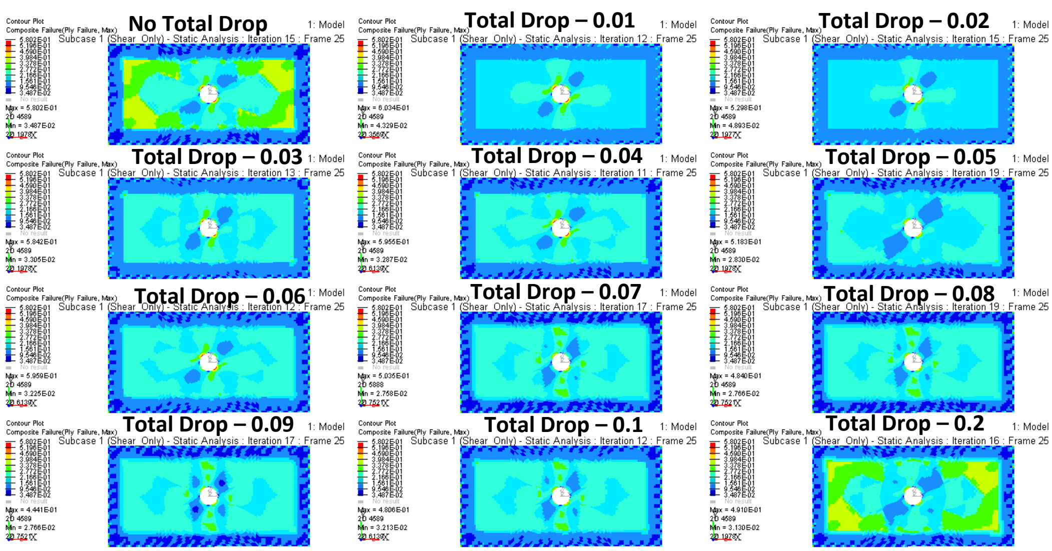


Figure 25: Failure criterion modes for shear loading from the case – Pressure 3 psi, Total slope 0.05

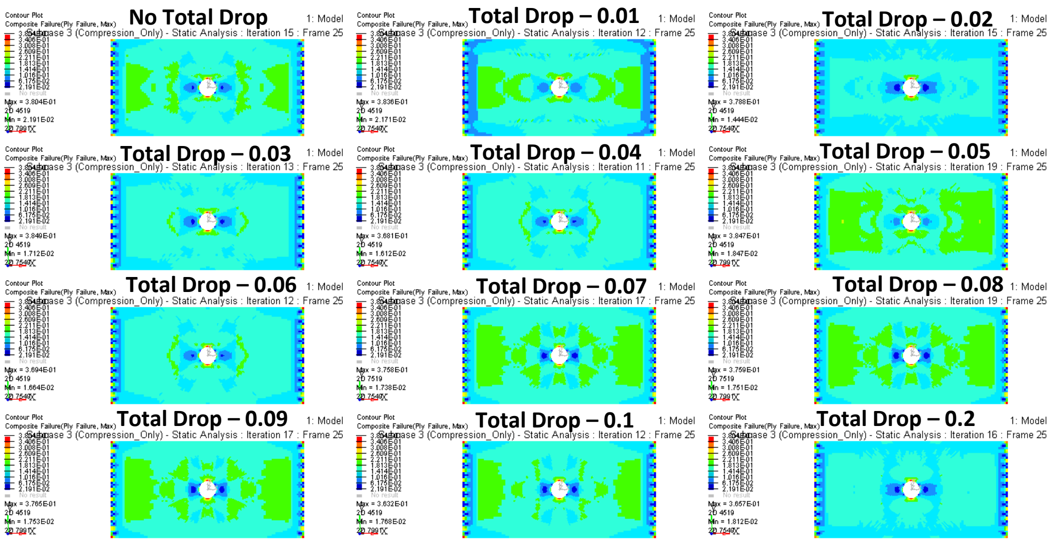


Figure 26: Failure criterion modes for compression loading from the case – Pressure 3 psi, Total slope 0.05

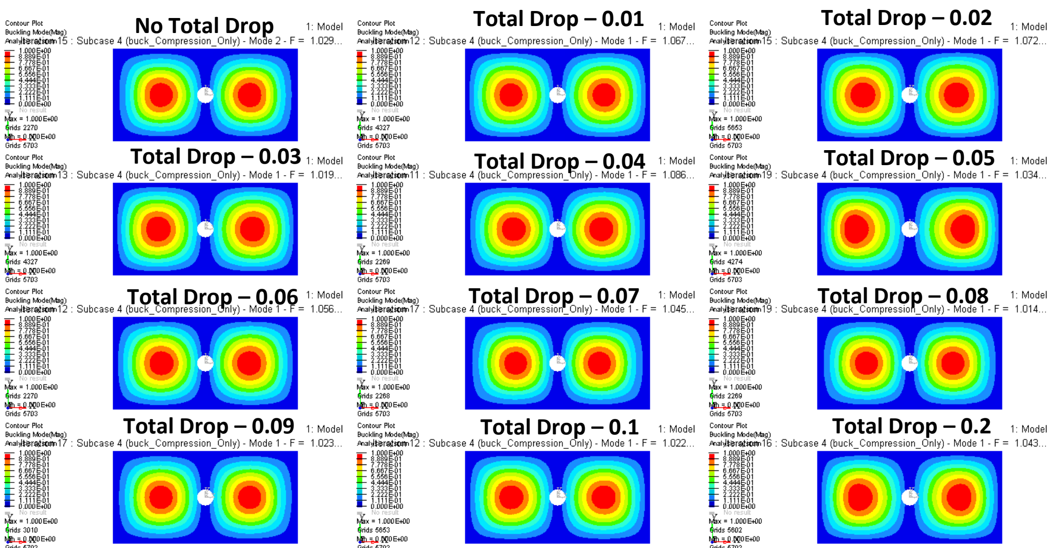


Figure 27: compression buckling from the case – Pressure 3 psi, Total slope 0.05

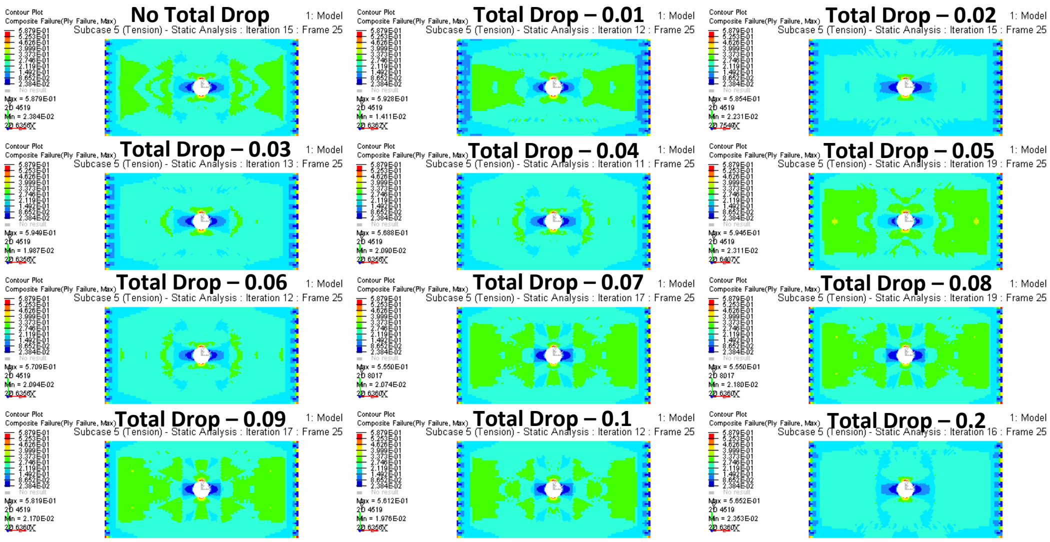


Figure 28: Failure criterion modes for tension loading from the case – Pressure 3 psi, Total slope 0.05

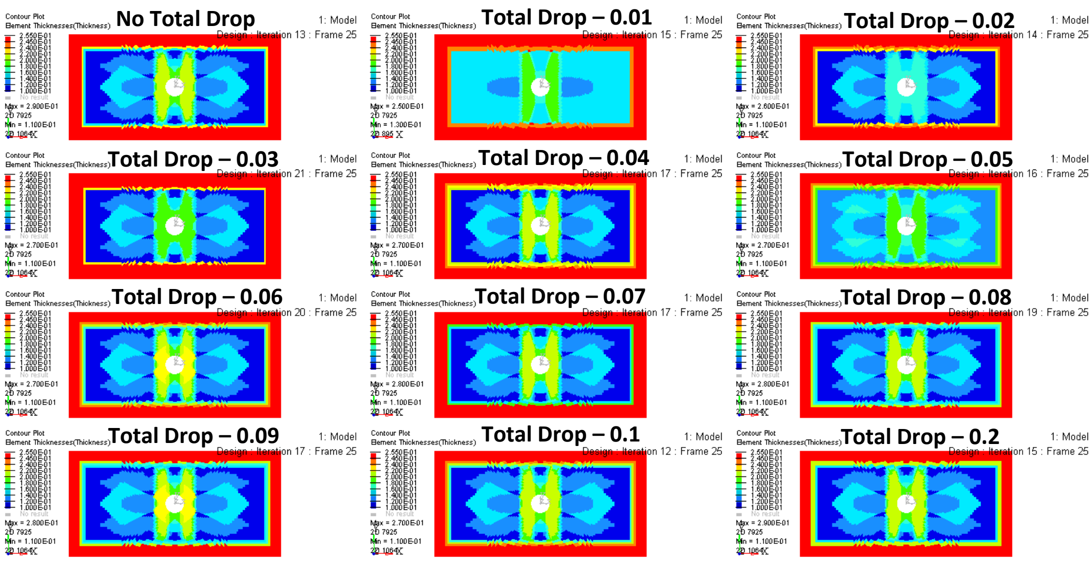


Figure 29: Size optimization results from the case – Pressure 3 psi, Total slope 0.1

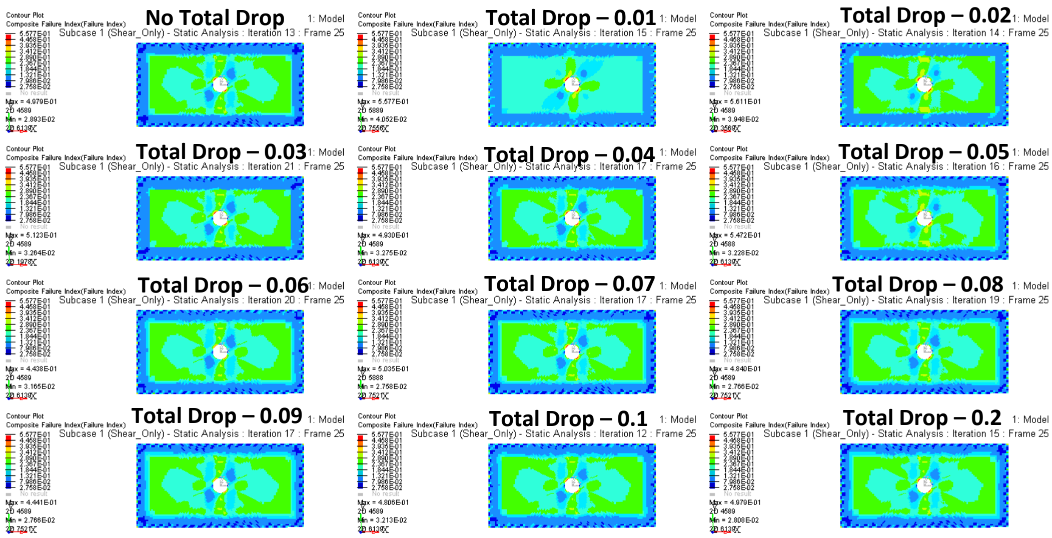


Figure 30: Failure criterion modes for shear loading from the case – Pressure 3 psi, Total slope 0.1

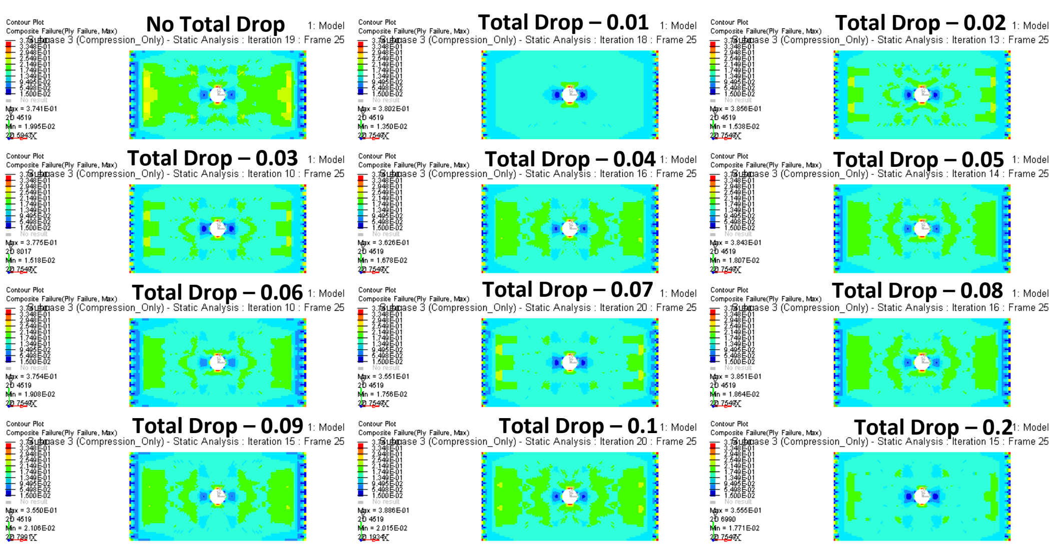


Figure 31: Failure criterion modes for compression loading from the case – Pressure 3 psi, Total slope 0.1

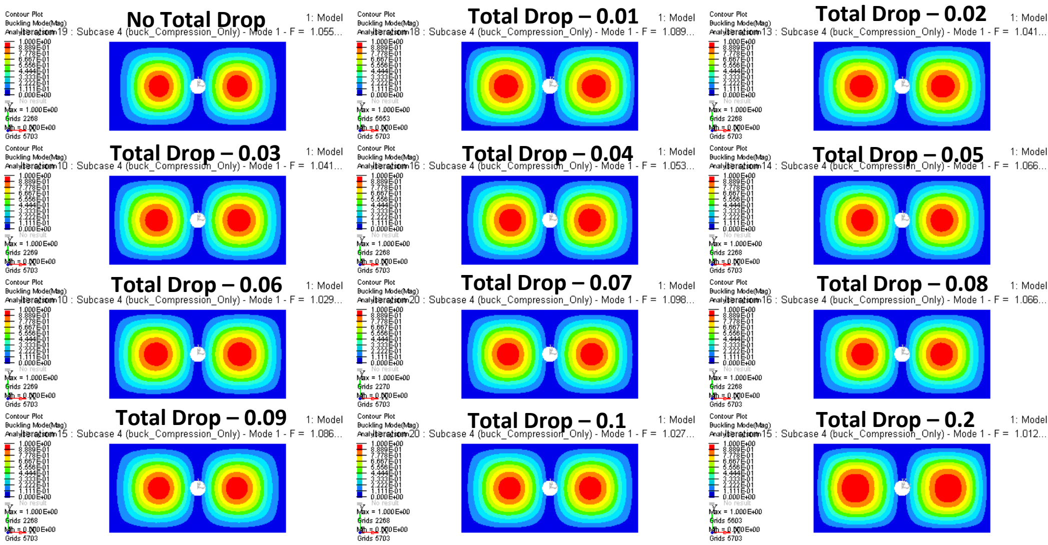


Figure 32: Compression buckling from the case – Pressure 3 psi, Total slope 0.1

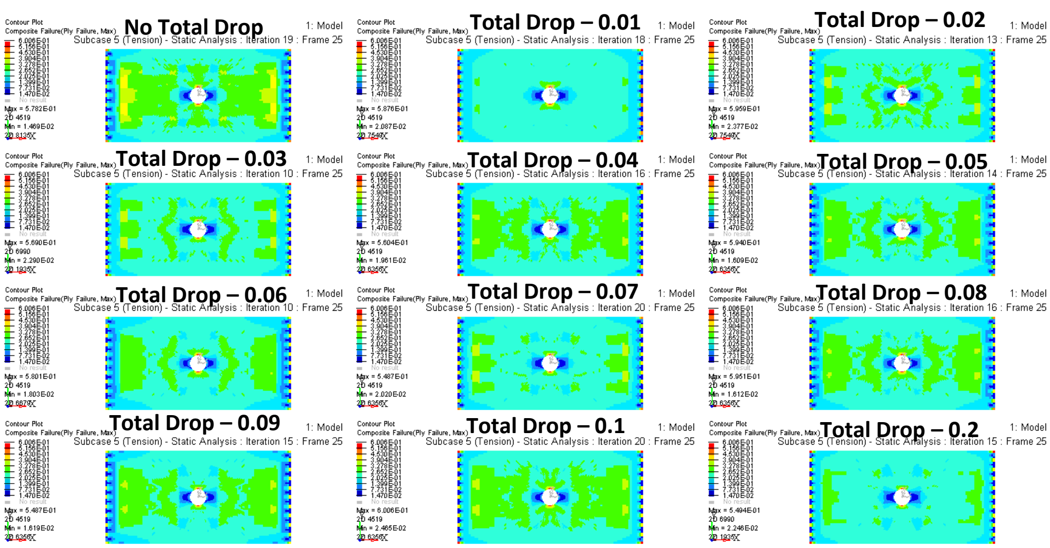


Figure 33: Failure criterion modes for tension loading from the case – Pressure 3 psi, Total slope 0.1

4.3 Three Zone Laminate Optimization

The first optimization study divides the plate into three zones defined by basic engineering judgment. The zones include a pad around the hole and a land region at edges for fastener bearing resistance as shown in Figure 3. Ply thicknesses are sized at each ply angle, 0º, 45º, -45º, and 90º, in the laminate. Ply drops at zone boundaries allow for three thickness zones in the laminate. The SMEAR option is used with symmetric stack on the composite property card to effectively homogenize the distribution of ply angles through the thickness of the laminate.

As discussed previously, this work explicitly models ply drops during sizing optimization to constrain the ply drop rate. Accordingly, 4 plies each are used to allow the land, shown in Figure 3(c), and pad regions (figure 3(b)) to gradually increase ramp thickness. Each ply has successively increasing width to allow the total drop (TOTDRP) constraint to gradually drop thickness. As discussed in section 4.2, sizing optimization was executed using twelve values for the TOTDRP constraint: none, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1 and, 0.2. The optimization added thickness to the pad and land regions where peak strains were seen in the constant thickness plate. The optimizer took advantage of the stepped ply zones for each total drop setting, although the sizing with no TOTDRP did not utilize all the steps. Plots of the max strain failure index at the final design for the three load conditions indicate regions of peak strain not only around the hole and at fastener locations but also at the pad zone boundary as shown in figure 34, 35, 36, 37. The addition of ply steps enabled the optimizer to reduce stress peaks at large changes in zone thickness as seen in the previous study[1,42]. Strain levels are generally low as buckling is the primary design driver. Figure 36 shows the buckling mode shape at the final design for the compression load case. The shear load case consistently resulted in large buckling eigenvalues and is not reported. Optimized panel weights, reported later in this study, were very similar and within the range of tolerances for model idealization and assumptions.

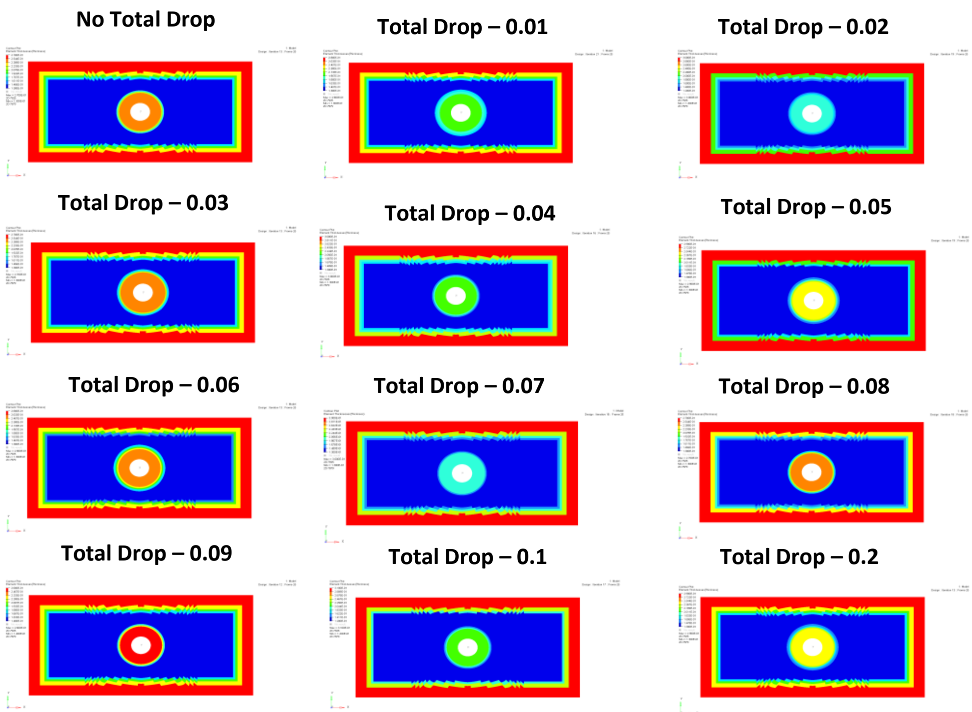


Figure 34: Element thickness trend after size optimization of three zone laminate with different total drop values

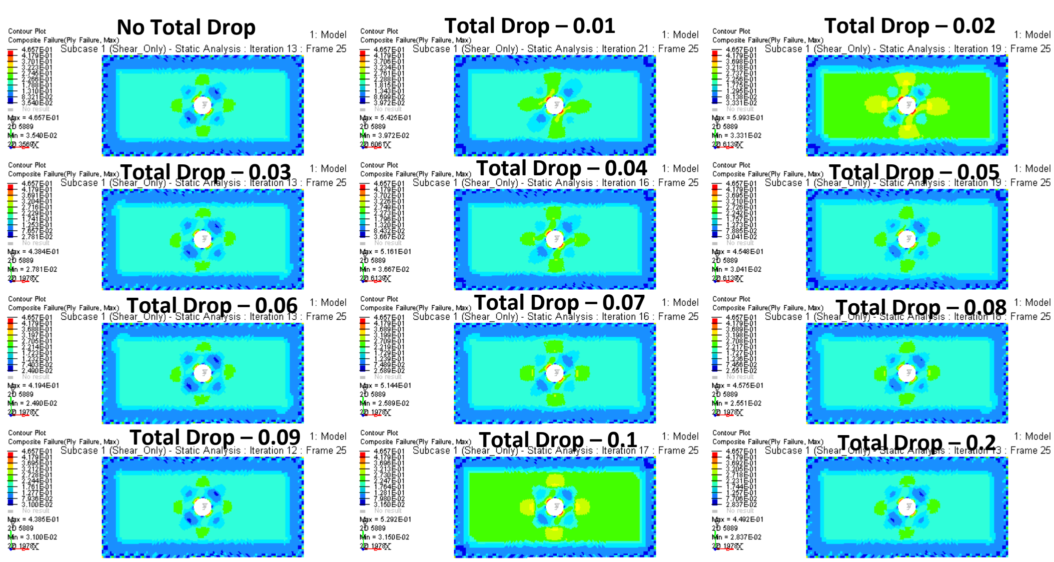


Figure 35: Failure criterion modes for shear loading for threezone laminate

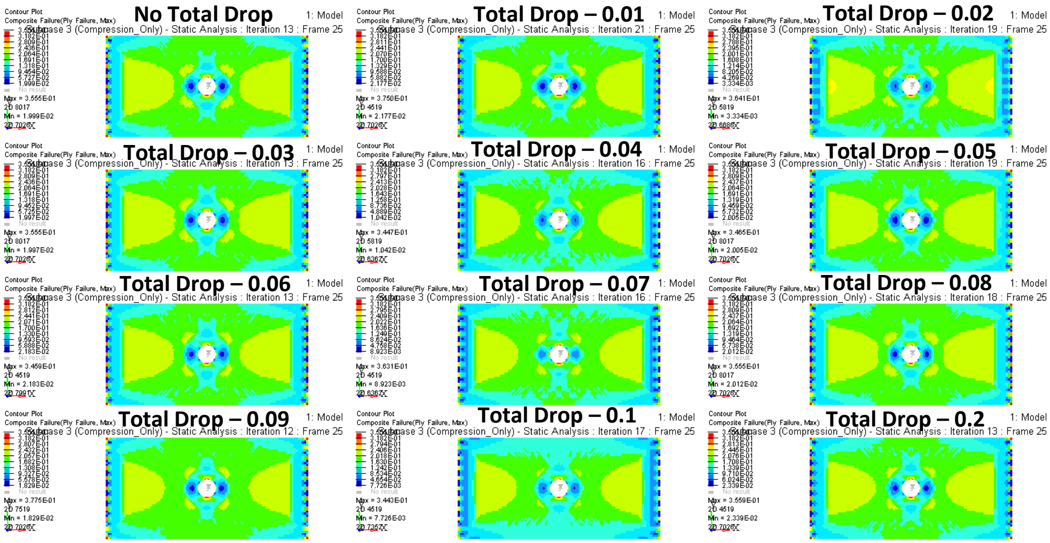


Figure 36: Failure criterion modes for compression loading for threezone laminate

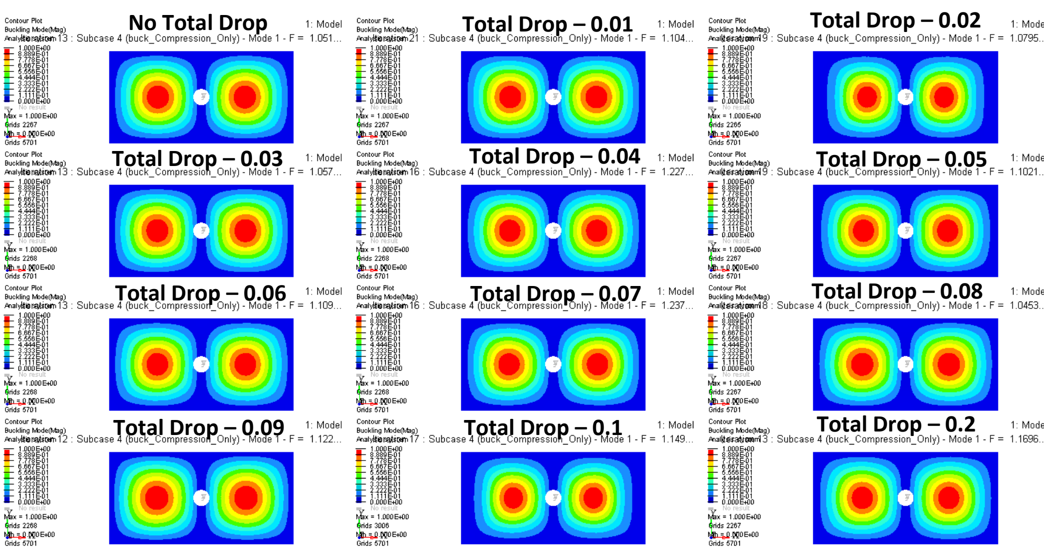


Figure 37: Compression buckling for threezone laminate

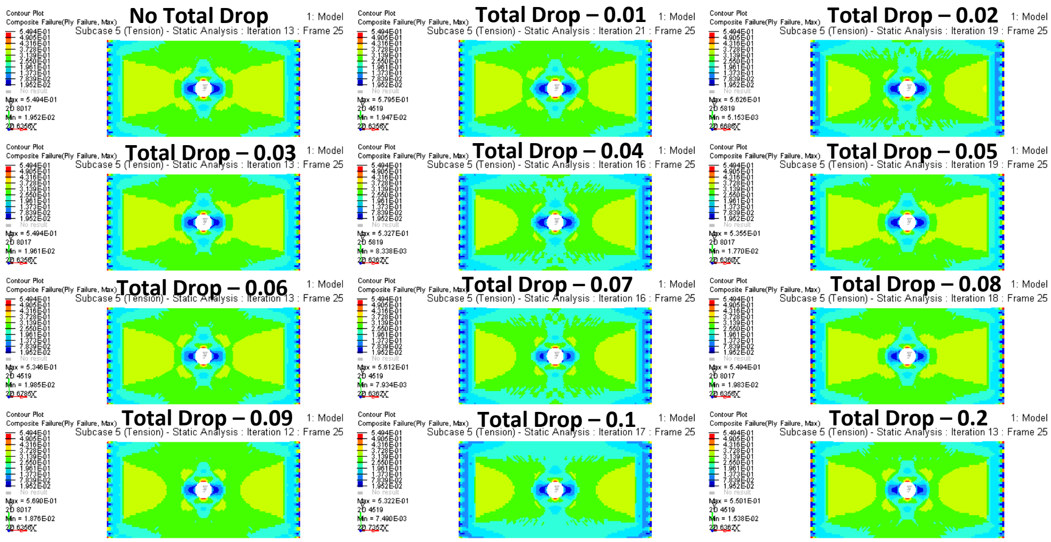


Figure 38: Failure criterion modes for tension loading on threezone laminate

4.4 Comparisons

From figure 39, It is evident that buckling values as high as 1.22 with an average of 1.068 from the chart which exceeded the buckling constraint value 1.02. From table below, mass variation of optimal zone plate is 5.3% from the lowest mass value. Average mass values of optimal zone plate vary by 2.6% from average mass numbers of three zone laminates. Mass values of optimized laminate fluctuates in similar range with threezone laminate. Based on the iteration history, it is evident that buckling constraint (see Appendix C) is driving the sizing of the laminate, this is due to the discreteness of the design constraints and limited design freedom.

TD / TS	0	0.01	0.02	0.03	0.04	0.05
0	2.130	2.118	2.058	2.113	2.090	2.099
0.1	2.061	2.163	2.087	2.101	2.095	2.085
0.05	2.092	2.122	2.162	2.089	2.111	2.048
TZ	2.117	2.147	2.110	2.130	2.194	2.138
TD / TS	0.06	0.07	0.08	0.09	0.10	0.20
0	2.077	2.073	2.053	2.062	2.075	2.101
0.1	2.073	2.117	2.084	2.106	2.091	2.085
0.05	2.089	2.063	2.097	2.086	2.087	2.108
TZ	2.171	2.178	2.105	2.139	2.155	2.210

Table 10: Mass values

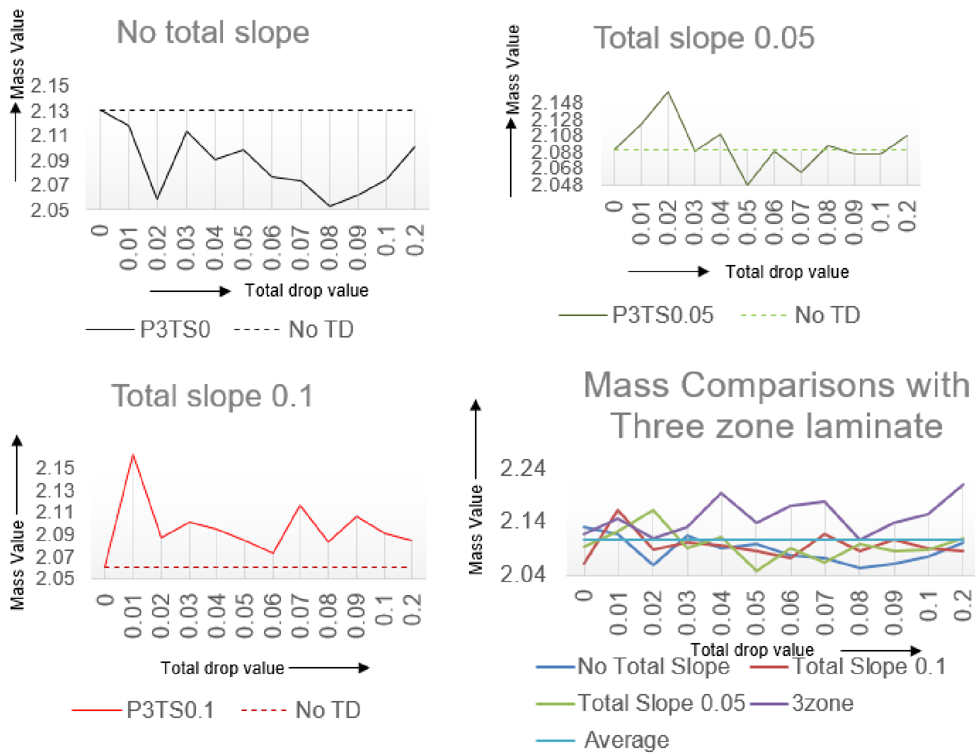


Figure 39: Mass vs Total drop plot for the case – pressure – 3 psi – total slope 0

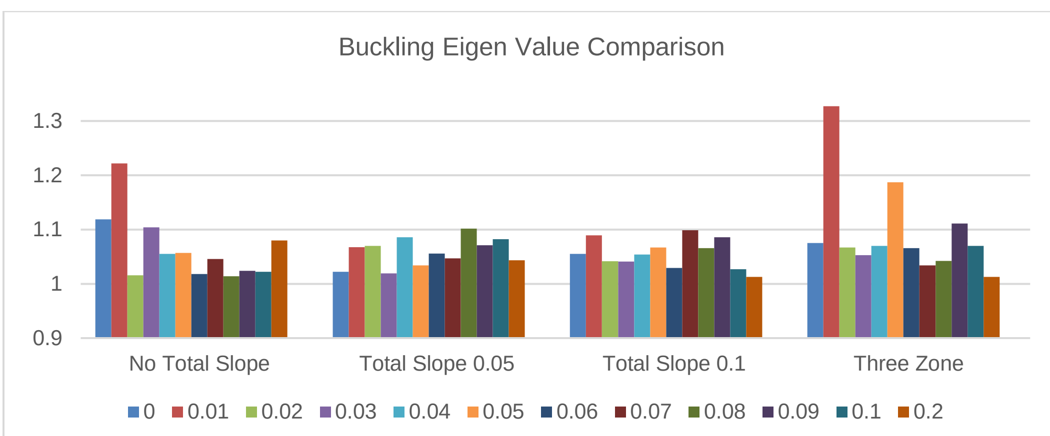


Figure 40: Buckling eigen values of all the cases

CHAPTER 5: CONCLUSION AND FUTURE WORK

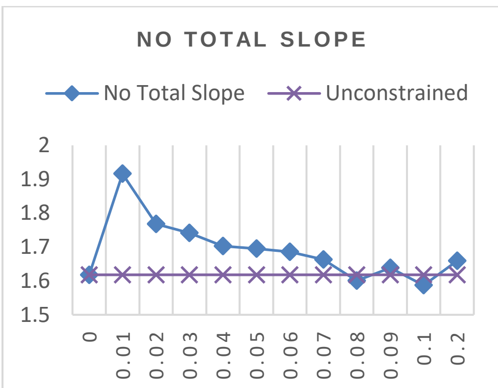
This study demonstrates that ply shape complexity can be adjusted to improve manufacturability while maintaining much of the weight savings that can be realized through automated optimization tools. Composite free size optimization can be used to optimally shape plies based on the loading environment prior to sizing the plies. For a strength critical design, significant weight savings can be achieved with this additional phase in the process. However, this weight savings drives additional complexity in the laminate configuration that can add additional cost to the component. The current work has applied a practical set of design and manufacturing criteria with the goal of quantifying the trade-off between weight and manufacturing complexity. While weight result trend with the variation of total drop values were inconclusive, a process for incorporating manufacturing criteria into free sizing-based composite laminate optimization methodology has been demonstrated. Only by applying the full set of design criteria and manufacturing constraints can the true potential of ply shape optimization to improve structural performance be determined. Realization of weight improvement requires the increased ply shape complexity to manufacture cost effectively. Current and future manufacturing controls within the optimization must be used to balance potential weight improvement with the economic cost of producing the more complex laminate

Currently, the research work has been proceeded to manufacturing phase where a laminate will be manufactured and studied. Since, this study is oriented towards methods of optimization, similar work will be implemented on complex structures like monocoque chassis. Additionally, scripts are in development to automate ply shape modification based on producibility rules. Finally, investigation is planned for integrating bonded stiffener design with free size optimization of a composite plate.

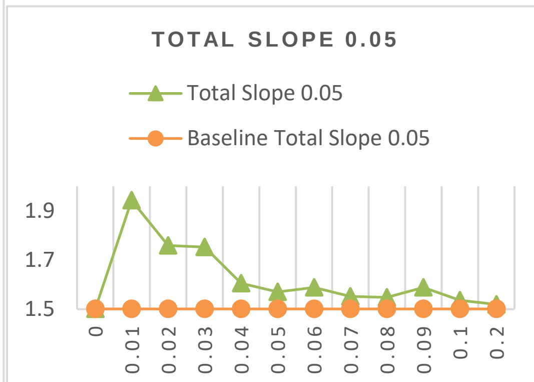
APPENDICES

APPENDIX A - MASS RESULTS WITHOUT BUCKLING CONSTRAINT

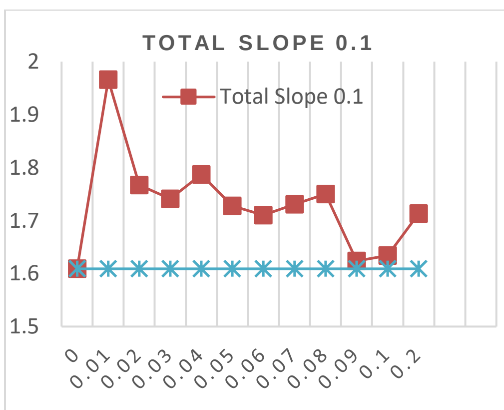
Similar optimization process has been conducted without the buckling constraint to observe the mass results. A pattern in the results of mass has been found which made it evident from figures 40, 41 and table 20 that buckling constraint has been driving the sizing of the laminate. All results displayed are obtained from free size optimization results with pressure 2 and total slope values – No total slope, total slope 0.05, total slope 0.1.



(a)



(b)



(c)

Figure 41: Results without buckling constraint

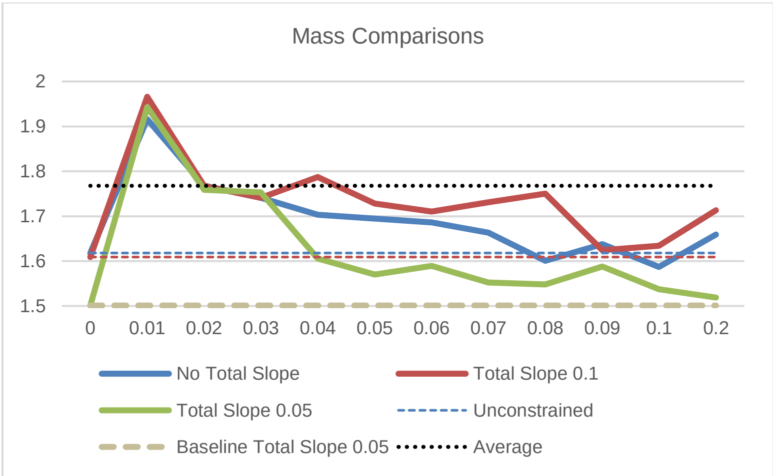


Figure 42: Result comparisons without buckling constraint

TS \ TD	No Total Slope	Total Slope 0.1	Total Slope 0.05
0	1.618	1.609	1.501
0.01	1.916	1.966	1.943
0.02	1.768	1.767	1.759
0.03	1.741	1.741	1.753
0.04	1.703	1.787	1.606
0.05	1.695	1.728	1.57
0.06	1.686	1.71	1.589
0.07	1.663	1.731	1.552
0.08	1.601	1.75	1.548
0.09	1.638	1.624	1.588
0.1	1.587	1.634	1.537
0.2	1.659	1.713	1.519

Table 11: Mass values without buckling constraints

APPENDIX B – FEM FILE STRUCTURE

```
$$
$$ Optistruct Input Deck Generated by HyperMesh Version  : 14.0.130.21
$$ Generated using HyperMesh-Optistruct Template Version : 14.0.130
$$
$$   Template:  optistruct
$$
$$
$$ optistruct
```

Control Card Data

```
$
RESPRINT=EQUA
OUTPUT,SZTOSH,YES
SCREEN OUT
 DGLOBAL = 4
CFAILURE(H3D,NDIV=1) = ALL
CSTRAIN(H3D,ALL,NDIV=1) = YES
CSTRESS(H3D,ALL,NDIV=1) = ALL
$$------------------------------------------------------------------------------$
$$                    Case Control Cards                                      $
$$------------------------------------------------------------------------------$
$$
```

Objective to minimize Mass

```
$$  OBJECTIVES Data
$$
$
$HMNAME OBJECTIVES       1objective
$
DESOBJ(MIN)=15
$
$
DESGLB       15
$
$
$HMNAME LOADSTEP              1"Shear_Only"       1
$
```

Load cases

```
SUBCASE       1
 LABEL Shear_Only
 SPC =        8
 LOAD =        2
 DESSUB =      16
$
$HMNAME LOADSTEP              2"buck_Shear_Only"       4
$
SUBCASE       2
 LABEL buck_Shear_Only
 SPC =        8
 METHOD(STRUCTURE) =        1
 STATSUB(BUCKLING) =       1
 DESSUB =      17
$
```

```
$HMNAME LOADSTEP              3"Compression_Only"       1
$
SUBCASE       3
  LABEL Compression_Only
  SPC =        8
  LOAD =        3
  DESSUB =      18
$
$HMNAME LOADSTEP              4"buck_Compression_Only"       4
$
SUBCASE       4
  LABEL buck_Compression_Only
  SPC =        8
  METHOD(STRUCTURE) =        1
  STATSUB(BUCKLING) =       3
  DESSUB =      19
$
$HMNAME LOADSTEP              5"Tension"       1
$
SUBCASE       5
  LABEL Tension
  SPC =        8
  LOAD =        4
  DESSUB =      20
$$------------------------------------------------------------
$$ HYPERMESH TAGS
$$------------------------------------------------------------
$$BEGIN TAGS
$$END TAGS
$
BEGIN BULK
DGLOBAL        4    AUTO    AUTO  OFFSET     ALL
+
$
$HMNAME PLYS              31100"PLYS_31100"
$HWCOLOR PLYS              31100       3
PLY     31100   2       0.005   0.0      YES     0.005
+       2
$
$HMNAME PLYS              34416"fastenerply3_90"
$HWCOLOR PLYS              34416       5
PLY     34416   2       0.005   90.0    YES     0.005
+       23
$$
$$  Stacking Information for Ply-Based Composite Definition
$$
$
$HMNAME LAMINATES             3"LAM_3"
$HWCOLOR LAMINATES             3       3
```

Load cases

Ply and
laminate stack

```
STACK   3      SYSMEAR 31100   32100   33100   34100   31200   32200
+       33200   34200   31300   32300   33300   34300   31400   32400
+       33400   34400   34401   34402   34403   34404   34405   34406
+       34407   34408   34409   34410   34411   34412   34413   34414
+       34415   34416
```

Ply and laminate stack

```
$$
$HMSET       2       2 "set2"
$HMSETTYPE        2 "formula"
SET     2       ELEM    LIST
+       1        THRU  8500
$
$
```

Ply shape information

```
$HMNAME OPTICONTROLS       1"optistruct_opticontrol" 1
$
DOPTPRM DESMAX  1000
$
```

Iteration limit

```
$HMNAME OPTITABLEENTRS       1"optistruct_tableentries" 14
$
DTABLE     F1xt     0.0    F1yt     0.0    F2xt  2000.0    F2yt     0.0
+          F1xc     0.0    F1yc     0.0    F2xc -2000.0    F2yc     0.0
+          F1xs  2000.0    F1ys     0.0    F2xs     0.0    F2ys  2000.0
+           Sym     2.0    diam    0.25 strnCmp  0.0042  BrgLim 80000.0
```

Allowable values data

```
$HMNAME DESVARS    31100fstosz
DESVAR     31100  fstosz0.005   0.0     1.0

$HMNAME DESVARS       3DCOMP3
DCOMP   3      STACK   3
+       LAMTHK  0.01
+       PLYPCT  0.0     .2      .6      BYANG
+       PLYPCT  90.0    .1      .6      BYANG
+       BALANCE -45.0   45.0            BYANG
```

Design variables

```
$HMNAME DVPRELS 31100   DVPREL1_31100
DVPREL1 31100   PLY       31100      T              0.0
+       31100   1.0
```

Design variables relationships

```
$$
$$  OPTIRESPONSES Data
$$
DRESP1  40      CStrn24 CSTRAIN ELEM            SMAP      4    6972
DRESP1  39      CStrn23 CSTRAIN ELEM            SMAP      3    6972
DRESP1  38      CStrn22 CSTRAIN ELEM            SMAP      2    6972
DRESP1  69      BucklingLAMA                 1
DRESP2  47      BrgLnd1       1
+       DTABLE      Sym    diam    F1xs
+       DRESP2       44     45      46
DRESP2  48      BrgLnd2       2
+       DTABLE      Sym    diam    F2xt    F2xc    F2ys
+       DRESP2       44     45      46
DRESP2  49      Per0          3
```

Responses

```
+       DRESP2        44      45      46
DRESP2  50      Per45          4
$
$HMNAME DEQUATIONS       2brg2
$
DEQATN  2       brg2(sym,diam,f2xt,f2xc,f2ys,thck0,thck45,thck90)=
+       rss((f2xt-f2xc),f2ys)/((sym*(thck0+2*thck45+thck90))*diam)
$
$
$HMNAME DEQUATIONS       1brg1
$
DEQATN  1       brg1(sym,diam,f1xs,thck0,thck45,thck90)=f1xs/((sym*(
+       thck0+2*thck45+thck90))*diam)
$
$
$HMNAME DEQUATIONS       3per0
$
DEQATN  3       per0(thck0,thck45,thck90)=(thck0/(thck0+2*
+       thck45+thck90))*100
$
$
$HMNAME DEQUATIONS       4per45
$
DEQATN  4       per45(thck0,thck45,thck90)=(2*thck45/(thck0+2*
+       thck45+thck90))*100
$
$
$HMNAME DEQUATIONS       5StrnIntcp
$
DEQATN  5       StrnIntcp(per0,per45)=(per45-per0)*17.5+6250
$
$
$HMNAME DEQUATIONS       6StrnTn
$
DEQATN  6       StrnTn(interc,strss)=((2900-interc)/80e3)*strss+interc
$
$
$HMNAME DEQUATIONS      10thck0
$
DEQATN  10      thck0(t1,t2,t3,t4,t5)=t1+t2+t3+t4+t5
$
$
$HMNAME DEQUATIONS       8MrgnStrn
$
DEQATN  8       MrgnStrn(strain,strainlim)=(strainlim)/abs(strain*1e6)
$
$
```

Design Equations

```
$HMNAME DEQUATIONS       9StrnMax1
$
DEQATN  9       StrnMax1(s1,s2,s3)=max(s1,s2,s3)
$
$
$
$$
$$  OPTICONSTRAINTS Data
$$
$
$HMNAME OPTICONSTRAINTS       1MrgStn11
$
DCONSTR        1       701.0
$
$HMNAME OPTICONSTRAINTS       2MrgStn12
$
DCONSTR        2       711.0
$
$HMNAME OPTICONSTRAINTS       3MrgStn13
$
DCONSTR        3       721.0
$
$HMNAME OPTICONSTRAINTS       4MrgStn14
$
DCONSTR        4       731.0
$
$HMNAME OPTICONSTRAINTS       5MrgStn21
$
DCONSTR        5       741.0
$
$HMNAME OPTICONSTRAINTS       6MrgStn22
$
DCONSTR        6       751.0
$
$HMNAME OPTICONSTRAINTS       7MrgStn23
$
DCONSTR        7       761.0
$
$HMNAME OPTICONSTRAINTS       8MrgStn24
$
DCONSTR        8       771.0
$
$HMNAME OPTICONSTRAINTS       9MaxStrn
$
DCONSTR        9       78-0.003  0.003
$
$HMNAME OPTICONSTRAINTS      10MinStrn
$
DCONSTR       10       79-0.003  0.003
$
```

Constraints

```
$HMNAME OPTICONSTRAINTS      13BrgLand2
$
DCONSTR       13      48        80000.0
$$---------------------------------------------------------------------------$
$$    HyperMesh name and color information for generic components              $
$$---------------------------------------------------------------------------$
$HMNAME COMP                  3"component1"
$HWCOLOR COMP                   3       4
$
$HMNAME COMP                  4"component2"
$HWCOLOR COMP                   4       5
$
$HMNAME COMP                  5"component3"
$HWCOLOR COMP                   5       6
$
$HMNAME COMP                  2"Middle Surface"        3 "CarbonTape" 4
$HWCOLOR COMP                   2      52
$

$

$
$HMNAME PROP                  3"CarbonTape" 4
$HWCOLOR PROP                   3       7
PCOMPP         3               18000.0     STRN
$$
$$  MAT8 Data
$$
$HMNAME MAT                   2"CarbonEpoxy" "MAT8"
$HWCOLOR MAT                    2       7
MAT8           22.2+7   1300000.0.3     750000.0        516000.00.056
+                            170000.0170000.06500.0  28000.0 10000.0
$$
$$---------------------------------------------------------------------------$
$$ HyperMesh Commands for loadcollectors name and color information $
$$---------------------------------------------------------------------------$
$HMNAME LOADCOL               5"Compression"
$HWCOLOR LOADCOL                5       5
$$
$HMNAME LOADCOL               6"Tension"
$HWCOLOR LOADCOL                6       5
$$
$HMNAME LOADCOL               7"Shear"
$HWCOLOR LOADCOL                7       5
$$
$HMNAME LOADCOL               8"Constraints"
$HWCOLOR LOADCOL                8       5
$$
$HMNAME LOADCOL               9"Pressure"
$HWCOLOR LOADCOL                9       5
```

Component Information

Card property

Material Property

Load collectors

```
$$
$$  EIGRL cards
$$
$HMNAME LOADCOL              1"EIGRL"
$HWCOLOR LOADCOL              1       7
EIGRL          1     0.0              2                           MAX
$$
$$  SPC Data
$$
SPC            8    4377       3     0.0
$$
$$  LOADADD cards
$$
$HMNAME LOADCOL              2"ShearLoad"
$HWCOLOR LOADCOL              2       3
$$
LOADADD       10     3.0     1.0       9
$
$$
$$  PLOAD4 Data
$$
PLOAD4         9       11.0
+            00.0     0.0     -1.0
$$
$$  FORCE Data
$$
FORCE          5    4417       01.0     -0.1    0.0     0.0
ENDDATA
```

Load collectors

Load bulk data

APPENDIX C – ALTERNATIVE SOLUTION

An alternative method for the optimization has been found when the bearing land region is set to non- design area while using PCOMPP property card[41.] Since, design freedom is further restricted, ply shapes formed are much smoother within the constrained design area. The mass results seem to vary in the similar range and varies within 6% to the lowest value. The results shown below in figure 42, 43 and Table 21 proves that the mass value range did not change from the results obtained from the above mentioned study.

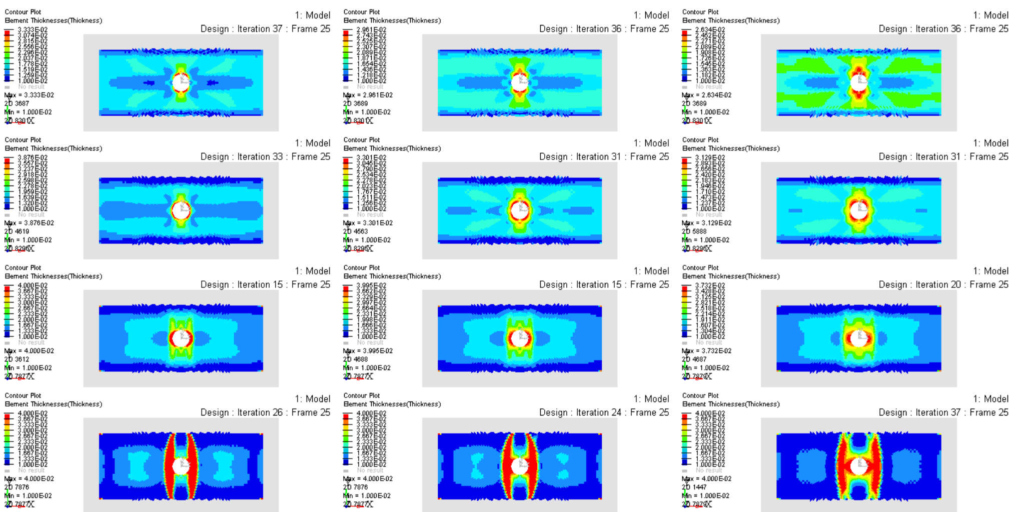


Figure 43: Free Size Optimization results

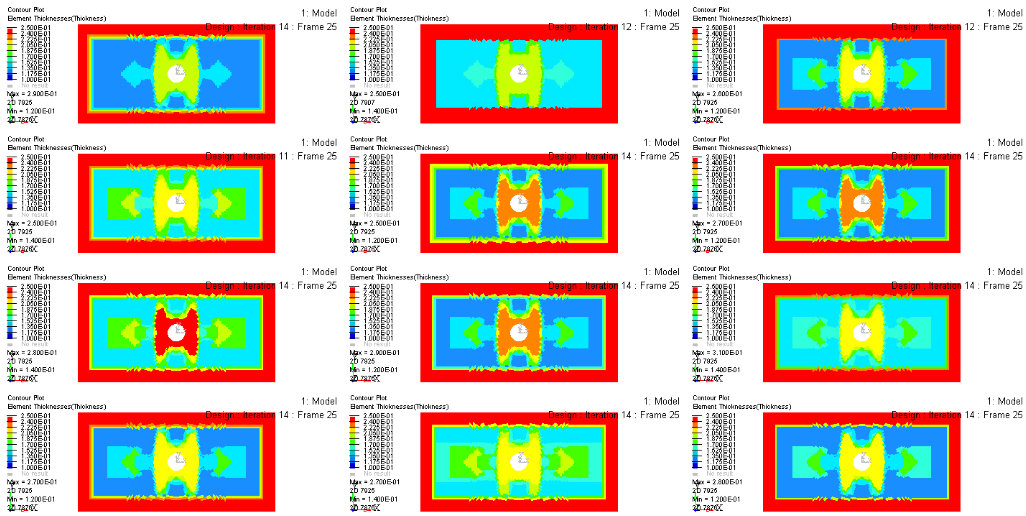


Figure 44: Pressure – 2 psi, Total slope – 0.05

TD / TS	0	0.01	0.02	0.03
0.05	2.107	2.161	2.134	2.153
TZ	2.117	2.147	2.110	2.130
TD / TS	0.04	0.05	0.06	0.07
0.05	2.119	2.105	2.110	2.138
TZ	2.194	2.138	2.171	2.178
TD / TS	0.08	0.09	0.10	0.20
0.05	2.155	2.142	2.112	2.089
TZ	2.105	2.139	2.155	2.210

Table 12: Mass comparisons in the alternative solution

APPENDIX D: MODEL SETUP IN ALTAIR - OPTISTRUCT

The finite elemental tool used for optimization is Optistruct, an optimizer tool developed by Altair Hyperworks. To implement the above-mentioned conditions, the user not only requires to know about the graphic user interface (GUI) but also needs to have a knowledge on finite elemental modeling of composite laminate. The composite structures, after defining the design area, properties such as PCOMP, PCOMPP can be used to specify the type of laminate that can be used in composite structure, material properties are added to this property, the optimizer after free size optimization creates 4 plies per orientation. However, user can change the number of ply bundles according to the requirements.

The first phase is a pre- free size optimization phase where the model needs to be created with constraints, loads and objective to create a topological layout of plies.

The Initial model setup follows basic geometry and material setup of the structure.

- Create a rectangular component with dimensions 20 x 10 inches with central hole of 1.75-inch diameter.
- Create three sets that cover the basic ply shapes, these sets will be used by the optimizer to assign the shapes of the plies in accordance with the orientation. The three shapes will be full, pad and land.
- Create a material property with the values as mentioned in table. The card image will be MAT8
- Create a property for assigning structural properties on the laminate. Assign the following values. The FT is the failure theory type, SB is the allowable inter-laminar shear stress.
- Assign the above-mentioned properties to the component and now the model is ready to get set for the loading environment

Next section follows the steps to assign the loading conditions.

Load step name	Analysis type	Subcase Definition
Shear_Only	Linear Static	SPC – Constraints LOAD – Shear load
Buck_Shear_Only	Linear Buckling	SPC – Constraints STATSUB – Shear_only METHOD - EIGRL
Compression_Only	Linear Static	SPC – Constraints LOAD – CompressionLoad
Buck_compression_only	Linear Buckling	SPC – Constraints STATSUB – Compression_Only METHOD - EIGRL
Tension	Linear Static	SPC – Constraints LOAD – TensionLoad
Pressure	Linear Static	SPC – Constraints LOAD – PressureLoad

Table 13: Loadcase information

To create constraints and objective in any optimization problem in Altair Optistruct, responses are created to drive them. The responses and relative objective and constraints created are given below

Response Name	Type	Sub-Type
Wcomp	Weighted comp	Loadsteps: Shear_only, Compression_only, Tension_only, Pressure
VolFrac	Volumefrac	total

Table 14: Responses for free size optimization

Objective and Constraint	Response	Value / type	Description
Objective: Minimize Compliance	Wcomp	Minimize	Assigning the objective to minimize compliance i.e, increase stiffness
Constraint: Volfraction	VolFrac	Upper Bound: 0.4	Removes 60% of the material by changing the element thickness

Table 15: Objective and constraint information for free-size optimization

Design variables in this phase manage the composite manufacturing constraints, laminate property is assigned, the type of desvar is PCOMP(G) and the values entered are given below.

Ply constraints	Values / type	Description
PLYTHK	ALL	Indicates that all ply thickness constraints are applied
PLYPCT	BYANG – 2, PANGLE(1) – 0 PPMIN(1) – 0.2, PPMAX(1) – 0.6 PANGLE(2) – 90,PPMIN(2) – 0.2 PPMAX(2) – 0.6	Ply percentage range of 20%-60% for the plies 0^0& 90^0 plies
PLYMAN	ALL PMMAN – 0.010	Minimum ply manufacturing thickness of 0.010 inch
BALANCE	BYANG BANGLE1 - -45.000 BANGLE2 - 45.000	Applying the balance constraint on ±45 plies
PLYDRP	TOTSLP – depends on the case	Ramp rate effect on total laminate with relative value

Table 16: Manufacturing constraints information for free-size optimization

The control cards are for the user to view the result and assigning the type of computation that the optimizer should carry on. The control cards are found in optimization and are mentioned as shown below.

Control Card	Type	Description
RESRINT	ALL	Prints all the values of the output in the output file
SCREEN	OUT	Screens the .out file
GLOBAL_OUTPUT_REQUEST	CSTRAIN – H3D CSTRESS – H3D CFAILURE – H3D	Forms a .h3d format file to display composite strain, composite stress and composite failure results
OUTPUT	FSTOSZ – YES	Decides the type of optimization to run

Table 17: Control cards in free size optimization

Once all the above settings are ready, go to analysis tab, select OptiStruct and choose

- Export options – Custom
- Run options – Optimization
- Memory options – memory default

Save the file with a name and click Optistruct, a display arises which runs the free size optimization. The next phase is pre- size optimization phase where all the ply shapes are developed. After editing all the plies, additional bearing land plies are added. In this stage, only change in the manufacturing constraints are the ply drop effect, total drop effect is induced with 10 different variants in values to study the drop effect. To add constraints, Design equations are added to induce them in responses. The final objective is set to minimize mass. Design equations mentioned in the section are incorporated in G.U.I. of HyperWorks and are described below.

Deqation	Equation Format	Description	Equation ID
thck0, thck45, thck90	thck0(t1,t2,t3,t4,t5)=t1+t2+t3+t4+t5 thck45(t1,t2,t3,t4,t5)=t1+t2+t3+t4+t5 thck90(t1,t2,t3,t4,t5)=t1+t2+t3+t4+t5	The thickness of the plies in each orientation is taken from dresp2 and are calculated in these equations	Deqatn 3 Deqatn 4 Deqatn 5
brg1, brg2	brg1(sym,diam,f1xs,thck0,thck45,thck90) =f1xs/((sym*(thck0+2*thck45+thck90))*diam) brg2(sym,diam,f2xt,f2xc,f2ys,thck0,thck45,thck90) =rss((f2xt,f2xc),f2ys)/((sym*(thck0+2*thck45+thck90))*diam)	The bearing stresses mentioned in section xxxx are incorporated, the values f1xs, f3xt,f2xc,f2ys,diam,sym are mentioned in DTABLE	Deqatn1 Deqatn2
per0, per45	per0(thck0,thck45,thck90)=(thck0/(thck0+2* thck45+thck90))*100 per45(thck0,thck45,thck90)=(2*thck45/(thck0+2* thck45+thck90))*100	The percentage of plies in the laminate for the calculation of bypass tensile strain	Deqatn6 Deqatn7
EbypT	EbypT(per0,per45)=(per45-per0)*17.5+6250	Tensile bypass strain mentioned in the section xx,Slope and intercept calculated from the values shown in table xx	Deqatn8
Elim	Elim(EbypT,strss)=((2900-EbypT)/80e3)*strss+EbypT	Linear Strain Interaction limit mentioned in section xx, Strain interaction value and bearing cutoff stress values are arbitrary	Deqatn9
MrgStrn	MrgnStrn(strain,Elim)=(Elim)/abs(strain*1e6)	Calculation of marginal strain to calculate stresses at peak locations	Deqatn10
StrnMax	StrnMax1(s1,s2,s3)=max(s1,s2,s3)	Implementation of maximum strain theory	Deqatn11

Table 18: Design Equations

These Design equations are related to design responses which are used for constraints and objective setup. The following table displays the response and the relative design equation as shown in table 17. These responses are assigned to respective constraints and objectives as shown in Table 18. Each ply requires design variable to vary the thickness with respect to objective and constraints. Free size optimization creates design variables and relationships for all the plies formed. Since, the limits formed are compliance based, the limits values are changed according to user decision, the following values are used in this work for all the design variable.

- Initial Value: 0.005
- Lower Bound: 0.00
- Upper Bound: 1.00

Response name	Type/ Values	Description
CSTRAIN	Response type: composite Strain Subtype: Normal Mode of selection: element	Assigned for calculating composite strains
MrgStrn	Response type: function dequation = MrgStrn	Inducing the marginal strains as response
MaxStrn	Response type: composite strain Subtype: normal Props: CarbonTape Excluding: elements: select bearing land region Subtype 2: maj. Principal Subtype 3: all plies	Respionse for max strain constraint
Min Strn	Response type: composite strain Subtype: normal Props: CarbonTape Excluding: elements: select bearing land region Subtype 2: min. Principal Subtype 3: all plies	Respionse for min strain constraint
CFailure	Response type: composite failure Props: CarbonTape Excluding: elements: select bearing land region Subtype 2: Max. Strn Subtype 3: all plies	Response to induce maximum strain failure theory
Buckling	Response type: Buckling Mode Number: 1	Response to include buckling criteria
Mass	Response type: Mass Subtype : total	Response for objective
Thck0 Thck45 Thck90	Response type: function dequation = Thck0 Desvars : Select full ply and bearing land plies per orientation	Response to calculate the thickness of bearing land region
Per0 Per45	Response type: function dequation = Thck0 Responses: Thck0, thck45, thck90	Calculation of ply percentages
EbypT	Response type: function dequation = EbypT Responses: Per0, Per45	Tension bypass strain calculation
BrgLnd1 BrgLnd2	Response type: function dequation = EbypT Responses: thck0, thck45, thck90 Table Entries : Select according to the direction	Subresponse for linear interaction strain limit. Bearing and bypass criteria induced by this equation
Elim1 Elim2	Response type: function dequation = Elim Responses: EbypT, BrgLnd1 or BrgLnd2	Linear Intertaction Strain limit

Table 19: response data in size optimization

As new fastener plies are created in this phase, respective design variables and design variable relationships must be added. The cards below are added.

Name	**Type / Value**	**Description**
MrgStn	Lower bound: 1.000 Response: MrgStn Loadsteps: Compression, Tension, Shear	Marginal strain constraint
MaxStn	Lower bound: 0.003 Upper bound: -0.003 Response: MaxStn Loadsteps: Compression, Tension, Shear	Maximum strain constraint
MinStn	Lower bound: -0.003 Upper bound: 0.003 Response: MinStn Loadsteps: Compression, Tension, Shear	Minimum strain constraint
BrgLnd1 BrgLnd2	Upper Bound: 80,000 Response: BrgLnd1 or BrgLnd2	Bearing stresses constraint
CFailure	Response: CFailure Loadsteps: Compression, Tension, Shear	Composite Failure criterion
Buckling	Lower bound: 1.02 Response: Buckling compression, Buckling Shear	Buckling constraint
Mass	Type: Min Response: Mass	Minimize Mass objective

Table 20: constraints and objective

Control Card	Description
DGLOBAL	Enables global search optimization to find a global optimum solution
OUTPUT - SZTOSH	Enables size to shuffle card to create model for shuffling optimization

Table 21: control cards in size optimization

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