Impact of fuselage cutouts on the stress and deflection behavior: numerical models and statistical analysis

Arz Y Qwam Alden [1, 2] **and Rabia Almamalook** [3, 4]

[1]Western Michigan University, Department of Mechanical and Aerospace Engineering, Kalamazoo, MI, USA
[2] University of Anbar, Engineering College, Mechanical Department, Ramadi, Al-Anbar, Iraq
[3] Western Michigan University, Department of Industrial Engineering, Kalamazoo, MI, USA
[4] Al Zawiya University, Department of innovation Engineer, Al Zawiya, Libya
arzyahyarzayy.qwamalden@wmich.edu, rabiaemhamedm.almamlook@wmich.edu

Abstract. Over the past several years, considerable studies have been made to understand the mechanisms of failure of composite structures and the effect of these mechanisms on the performance of structures components made of composite materials. The compressive response of composite materials has received considerable attention due to their significance in the aerospace industry and the complexity associated with compressive failure. Failure criteria for anisotropic composite materials, which have different strengths in tension and compression, have attracted numerous researchers over decades and it is still today an important research topic. The goal of this study is to create a validated model to evaluate the effect of cutout shape, size, and the lamination angles of layers on the failure criteria of the fuselages. To achieve this objective, finite element method and statistical analysis have been used. The results show that the various analytical and empirical approaches have been used to study the failure capability of the fuselage structure. The model is applicable to the air transport industry. The proposed model has been validated against the known shape of an aircraft.

Key words: Fuselage Cutouts, Deflection Analysis, Stress, Aerospace Industry.

1. Introduction

Several prior studies, development, and design communities assess the mechanisms of failure of composite structures and the effect of these mechanisms on the designing of structures components made of composite materials. The compressive response of composite materials has received considerable attention due to their significance in the aerospace industry and the complexity associated with compressive failure. Failure criteria for anisotropic composite materials, which have different strengths in tension and compression, have attracted numerous researchers over decades and it is still today an important research topic [1-8]. However, Tsai–Wu criterion is used in this study.

Fiber reinforced composites owns outstanding features, such as high specific strength, high specific modulus, desirable performance and integral forming easily, so, it has been widely used in the field of Aeronautics, Astronautics and Automotive. This application could remarkably reduce the weight and improve flight performances. Many commercial aircrafts, such as the Boeing 787 Dreamliner (50%), Airbus A380 (20%), and A350 (50%) have been produced by utilizing advanced fiber placement technology [9]. The utilization of composite materials in airplane structures is continuously developing. The manufacturing type utilized for the exciting composite airframe structural parts is not liable to be used for these structures. Design philosophies and manufacturing technology ought to be changed to accomplish the formation of composite fuselage structures. Cutouts have a downside on the stresses, so, the impact of these cutouts has to be studied. Utilizing the outcome that the stress situation in the facings compares to that of a flat plate, the window region has been further analyzed with level curved plate models to learn how the impact of cutouts. The influence of cutout shape, cutout size, and angle of lamination have been implemented in this study.

There are two different approaches to study the behavior of composite; first: micromechanical handles the composite material combination of different materials. Second: derives the average property considering the properties of a single matrix of unit cell [10]. In previous years, there are several new materials have become accessible and that give the impression of being suitable for use in airplane structures. These materials can be classified into: composites, metals and combinations of these two, the fiber metal laminates. Composite materials are materials made from two or more constituent materials with significantly different physical or chemical properties. When combined, produce a material with characteristics different from the individual components. They are found in many types of structural and aeronautical weight sensitive applications, such as aircraft wings, horizontal and vertical stabilizers and missile cases, therefore; it is necessary to investigate their static behavior under different combination of layers and types of cutouts. Advantages of the directional properties of advanced composites could be completely used by changing the fiber angles of lamina consistently from point to point, which resulting in stiffness properties that change as a function of location, and so this laminate is termed variable stiffness composite panels. In this way, it is possible to distribute the loads, in order to make a satisfactory response to planar stress varieties, furthermore redirect the loads from the most delicate districts, for example, openings and notches, reaching high proficiency of composite structure [9]. A new resin system has been developed within the first group. Moreover, a new way of producing aircraft structures with thermoplastic resins. It offers an extremely good temperature and chemical resistance. These resins offer a high specific mechanical property with clean, high speed produce ability when combined them with continuous, strong and stiff fibers. Airframe engineer's vision any cutouts in airframe structures with disfavor because the required reinforcement of the cut-out increases both of costs and weight to the overall design. Moreover, the shape and size of the cutout is a difficult process since it is an area of stress concentration, a problem area for basic strength, stiffness and life requirements and there is insufficient design data. The cutouts are essential in airframe structures to provide the following;

- Fuel access cutout at the bottom skin of wing and fuselage.
- Landing gear opening and retracting at the bottom skin of the wing or fuselage.
- Lightening holes in webs.
- Accessibility for final assembly and maintenance (e.g., manholes in wing lower surfaces, crawl holes in wing ribs, etc.).
- Inspection for maintenance (medium sized cutouts called hand holes).
- Window cutout in fuselage.

There is no guarantee for success in both financial and technical to the introduction of fiber reinforced plastics in the primary structure of the wing and fuselage of large civil aircraft, ‘Figure 1’. Therefore, the development of metal, stiffened skin, aircraft structures into composite structures backed off by the commercial danger included with this change. Truth be told, there are a lot of reasons to supplant aluminum as essential aircraft material by composites: Firstly, manufacturing of composite materials needs only cutting, pressure, and heating devices. Another reason is the fatigue of aluminum, for instance resulting in the current ‘ageing aircraft’ problem. This problem perhaps can be solved by coming of composite materials. The aluminum corrosion and an environmental effect on composites is the third reason. In fact, it seems the environmental effect on composites are less severe than the effect on the currently used aluminum alloys. The possibility to save weight with a good specific property of composite materials is the final reason. On a weight premise composite material can be stiffer and/or stronger than the normal materials and they can be tuned, offering the chance of local alterations in material strength and stiffness. In order to maximize the probability of a successful introduction of composites should not be thinking about weight saving of 30% as a straightforward major target, but as an added benefit. From the previous discussion, it is better to emphasize on reduction of production costs and lower inspection and maintenance costs. Finally, it becomes clear that composites can contribute to a further improvement of aircraft structures [11]. The aim of this paper is to study the effects of aircraft fuselage with window cutouts on the stress and deflection analysis

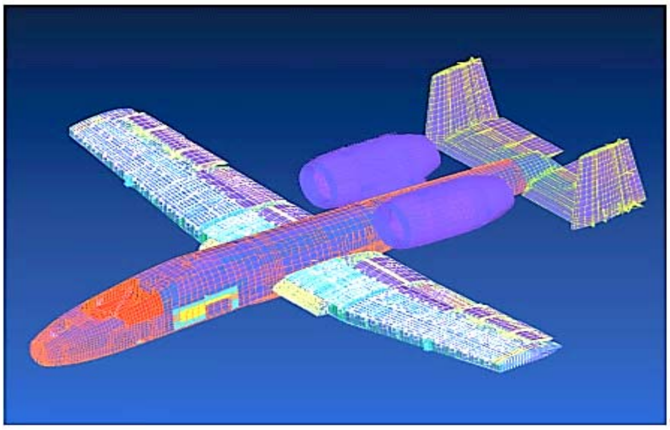


Figure 1. Aircraft structure

2. Methodology

2.1 Geometry Configuration

After designing model, next step to discretize the geometry into small elements so that the analysis of the window cutout can be carried out accurately. The window Aircraft Fuselage considered for the study is shown in ‘Figure 2’. An aircraft fuselage structure must be capable of withstanding many types of loads, and stress concentrations near cutouts are of particular concern. The main difference between curved and flat plates weakened by a hole and loaded with internal pressure or uniform axial loads. The magnitude of these stresses relative to the applied stresses depends not only on the shape of the hole and the plate width, but also on the geometry of the shell. This geometry may be described by two parameters:

- t / R: the ratio between the shell-thickness and the radius of the cylinder
- a / R: the ratio between the radius of the hole and the radius of the cylinder

The symbols t, L, R, r, b and a are illustrated in ‘Figure 2’.

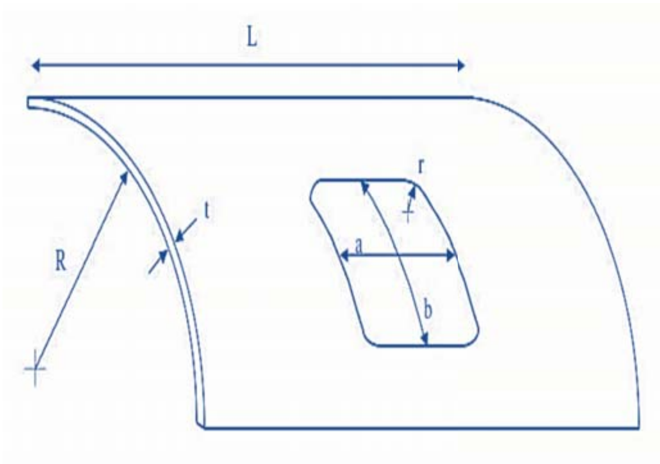


Figure 2. The geometry parameters describing the curved shell [12]

2.2 Material Specification

In this study, the material considered for window Aircraft Fuselage of the structure is steel. Table 1 shows the properties of the materials was used.

Table 1. Mechanical properties of a unidirectional lamina [13]

Property	Material properties [a]
Longitudinal elastic modulus (E1)	172.4 GPa
Transverse elastic modulus (E2)	6.9 GPa
ν12 = ν13 = ν23	0.25
Shear modulus (G12)	3.45 GPa
Shear modulus (G13)	3.45 GPa
Shear modulus (G23)	1.38 GPa
Ultimate longitudinal tensile strength (Xt)	207 KPa
Ultimate longitudinal compression strength (Xc)	-82.8 KPa
Ultimate transverse tensile strength (Yt)	3.45 KPa
Ultimate transverse compression strength (Yc)	-10.3 KPa
Ultimate in-plane shear strength (S)	6.89 KPa

[a] All material properties are in SI system of units

2.3 Finite Element Analysis (FEA) Approach

The finite element method is a numerical technique for solving problems which are described by partial differential equations or can be formulated as functional minimization. A domain of interest is represented as an assembly of finite elements. Approximating functions in finite elements are determined in terms of nodal values of a physical field which is sought. A continuous physical problem is transformed into a discretized finite element problem with unknown nodal values. For a linear problem, a system of linear algebraic equations should be solved. Values inside finite elements can be recovered using nodal values

The finite element analysis approach suits this design problem well because it allows for thorough examinations of the structural behaviors of the windows fuselage under various loads without the risk of damaging a prototype or the need to modify it. The finite element analysis approach also puts significant challenges onto the shoulders of the practitioners: the finite element model and boundary conditions must be accurate enough to capture the physics, yet they must also be of relatively low computational cost in order to allow for rapid changes in the design.

2.4 Finite Element Model of the Window Fuselage

Finite element analyses are conducted for the stress concentration analyses of perforated aluminum plates Modeling composite laminated plates requires extra attention in defining the properties of the plate, including number of layers, thickness and fiber orientation of each layer, as well as mesh sizing, especially near the cutouts. The purpose the finite element model is to make a model that behaves mathematically as being modelled and creates appropriate input files for the different finite element solvers. This study describes a conceptual design and analysis of fuselage structure for Lockheed L-1011 commercial aircraft fuselage [14]. ABAQUS (Version 2016, Dassault Systems, Simulia Corp., Johnston, RI, USA) was used to create finite element models of the fuselage. Some of design parameters are studied in this study such as lamination angle (θ°), the hole dimensional to a width of the plates (D/2b) ratio, and types of the cutout. Maximum stresses and deflections at point A are obtained for flat plates which contain different types of cutout subjected to pressure load. Table. 2 shows the dimensions of the model that are used**.** Where (D) presented diameter of the circular (C) and the length of side of the square (S), longitudinal rectangular (LR), and transverse rectangular (TR) cutouts as shown in the following 'Figure 3'.

Table 2. Dimensions of the model

Name of dimensions	Measure
Radius of Curvature	R= 2.54 m
Skin Wall Thickness	t= 0.0016 m
Window Dimensions	a= 0.254 m, b= 0.381 m
Window Corner Radius	r= 0.0508 m
Square Section Span Length	L= 0.762 m

Figure 3. Types of cutouts

2.5 Loads and Boundary Conditions:

A 3D modeling space with solid, continuum, and deformable elements. The loads and boundary conditions along with the finite element model are shown in the 'Figure 4'. One load case, was applied to the model: internal pressure (62052.8 Pa). This load will essentially create the required bending moment [13]. Based on cylindrical pressure vessel theory, the loads will be calculated. As such, the inner pressure will cause about a circumferential and a longitudinal stress in the window, which can be applied at the edges of the structural part being displayed. Also, internal pressurization is a symmetrical load case. Due to the behavior of the simulation and the predicted small displacement of elements, a static (general) step was created. Abaqus CAE automatically generate default field and history output request once a step is created. To study specific parameters in Abaqus CAE, go to Model Tree, Field Output Request, then determine the requirements. Due to symmetry, a quarter of the plate has been taken to study, 'Figure 4'. Using mesh control, a quad element shape was assigned to the part using a structured technique. Abaqus CAE, by default, color parts green due to a structure mesh. All parts were assigned an S4R element type using a linear geometric order and shell family.

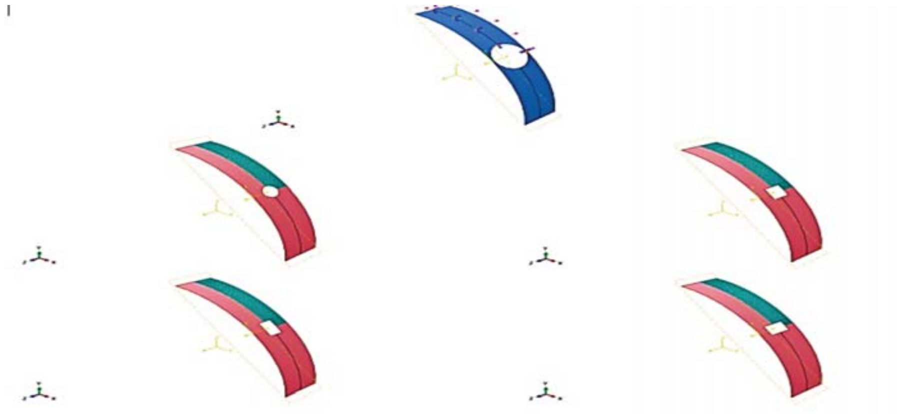


Figure 4. Boundary conditions and mesh

3. Results and Discussion Approach

Due to pressurization in the fuselage will experience the hoop stress and longitudinal stresses. The window cutouts in the fuselage are in the circumferential direction. Therefore, the hoop stress is more critical than the longitudinal stress in the case of the stiffened panel with window cutout.

3.1. Finite Element Model and Stress Analysis in Window Fuselage

3.1.1 The Effect of (D/L) Ratio of Cut- Outs in Laminated Plates

Nine radius ratios are considered in this study: D/L = 0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8 and 0.9 respectively for each cut-out shapes. Figure 5 and Figure 6 show the effect of (D/L) ratio on the stresses and deflections at the point (A) of the plate that contains central holes (circular, square, longitudinal rectangular, and transverse rectangular).

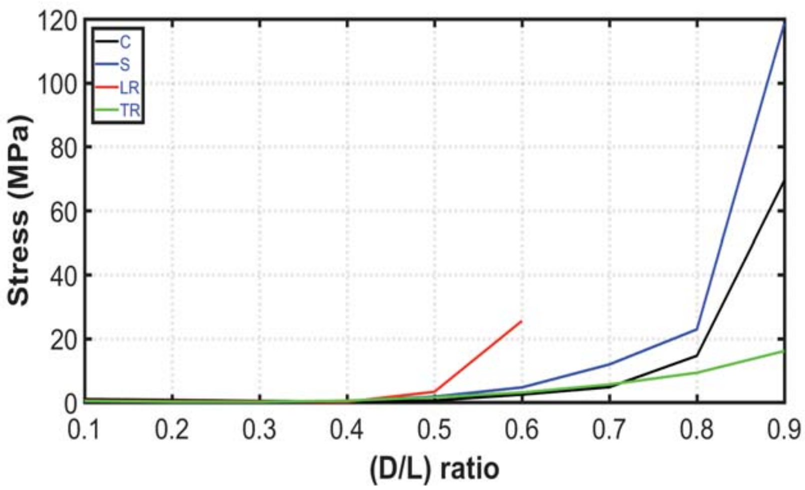


Figure 5. Effect of (D/L) ratio on the stress

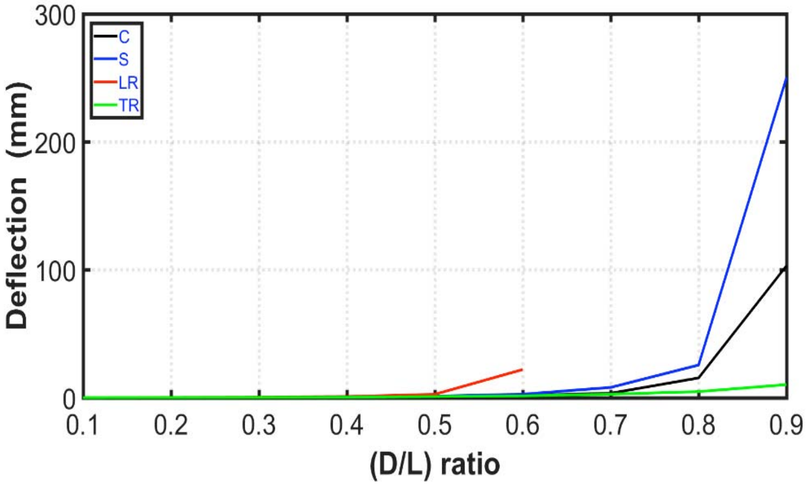
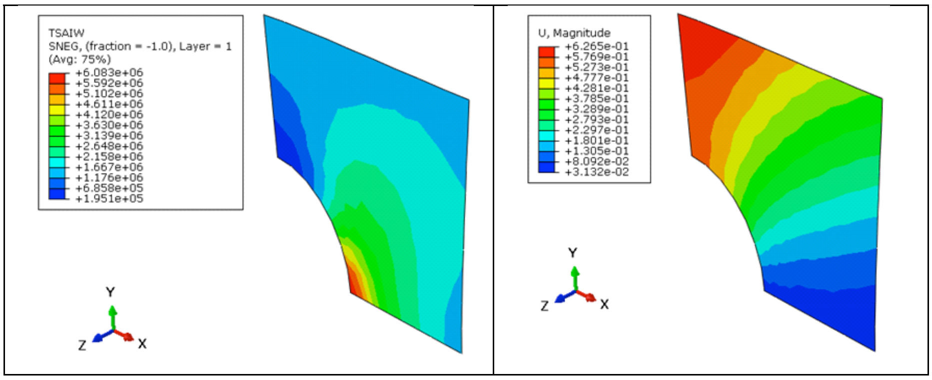


Figure 6. Effect of (D/L) ratio on the deflection

The value of stresses affected by (D/L) ratio. It can be noted that from the table 2, it can that the minimum stress occurred at (D/L=0.4) for circular and longitudinal rectangular, while for square and transverse rectangular occurred at (D/L=0.3). The change of stress becomes very high after these ratios at all types of holes. The value of deflection (U) increases with increasing of the (D/L) ratio. Both of the shape of cutout and (D/L) ratio have an effect on the values of stress and deflection. To visualize the stress patterns, stress and deflection contours of four types of cut-out with D/L = 0.4 and lamination angles 0^{o} are shown in 'Figure 7'.



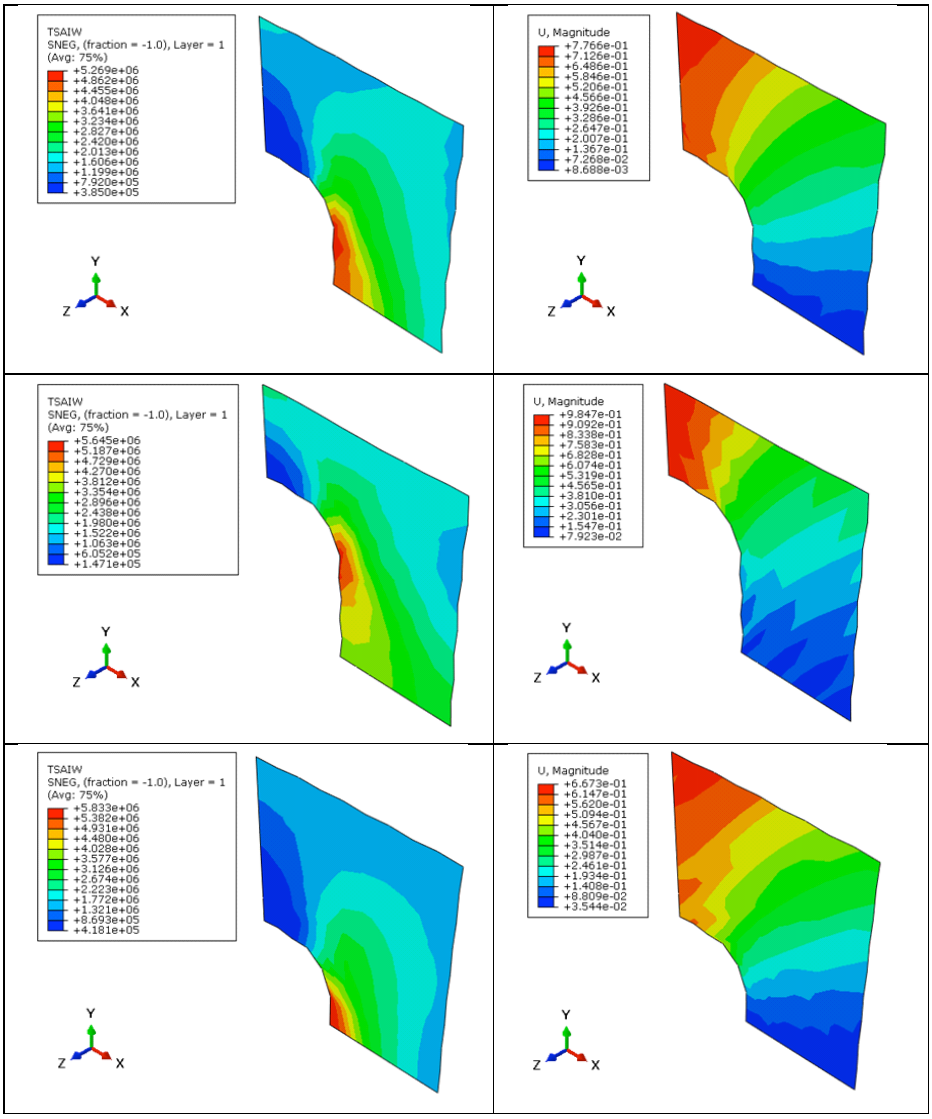


Figure 7. Stress and displacement contours of the model

3.1.2 Lamination Angle of the Cut-Outs

The effect of lamination angle (θ°) of layers in laminated plates represents the point of attraction of this type of composite materials, since the stiffness of the laminated plate could be changed by changing only the angle of laminate, thickness, aspect ratio, and number of layers. This section discusses the stress analysis results by considering the lamination angle of the cut-outs. In the cases of the square cut-out, ten lamination angles are considered 0°,10°,20°, 30°,40°, 50°,60°,70°,80°and 90°, while ten angles are considered in the case of the triangle cut-out. Table 3, 'Figure 8', and 'Figure 9' show the effect of the lamination angle (θ°) on the maximum stresses s and deflection at the point (A) of the plate at the best ratio of (D/L) ratio. A plate contains a central hole (circular, square, longitudinal rectangular, and transverse rectangular) under the same boundary conditions. Changing the angle of laminate effect on the stiffness of the laminated plate.

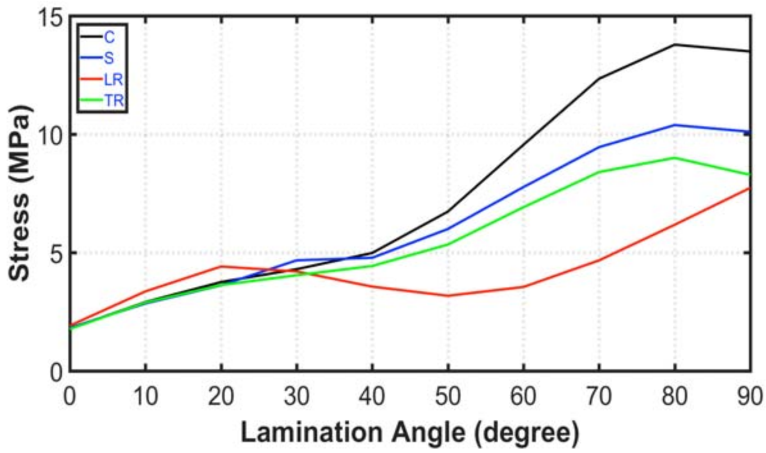


Figure 8. Effect of lamination angle on the stress

As a result, we can see that many differences occur in the maximum stresses, depending on the lamination angles. The fibers carry the applied load when put at (θ°) equal to (0°,), while the matrix carries the load when put at (θ°) equal to 90°. For a symmetric plate subjected to axial constant applied load, the maximum value of stress occurs in lamination angle (90°) for the longitudinal rectangular cutout. In addition, we can see that while the maximum value of stress occurs in lamination angle (80°) for the circle, square, and transverse rectangular respectively as shown in 'Figure 8'. The maximum value of stress and deflection is affected by changing the lamination angle (θ°).

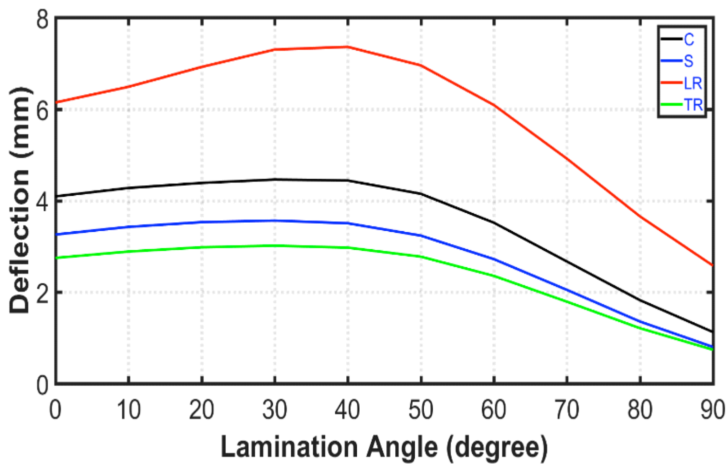


Figure 9. Effect of lamination angle on the deflection

For all types of cutouts, it is noted that the maximum deflection occurs at a lamination angle (40°), as shown in 'Figure 9'. In order to study the effect of presence of circular, square, longitudinal rectangular, and transverse rectangular holes on the maximum values of stress and deflections of a symmetric square plate subjected to axial constant applied load, table 3 can be predicted from 'Figure 8' and 'Figure 9'. However, for all of the cases consistently, the stresses increase as lamination angles increase. As a result, we can see that many differences occur in the maximum stresses, depending on the lamination angles.

3.2. Statistical Analysis

Understanding the underlying relationship between stress outcomes and factors leading is very important in addressing the problem of frailer. This research combines statistical regression method to identify the main factors associated with stress outcomes. This work relies on the analysis of data to study effect ratio and cut outs in stress. In this study we consider a linear regression approach for the development of a model.

3.2.1 Description of Data

The data has 36 observations and, has two independent (with (D/L) ratio and cutout type factored) and one response variable(stress), which was determined after examination of the data. Summary descriptive statistics of the response variable stress and other variables, are shown table 3:

Table 3. Descriptive statistic

Variable	N	N*	Mean	SD[a]
Cutout type	36	0	4.10	1.134
(D/L) ratio	36	0	0.5	0.2686
stress	33	3	0.0436	23.55

[a]SD = Standard Deviation

3.2.2 Studying the Effect of (D/L) Ratio and Cut-Out in Stress Statically

This study has used General Linear Model(GLM) to analysis date via MINITAB. Iko90\ the ANOVA procedure uses an F test to assess significance. In the partial method, each independent variable or ANOVA factor in the model is adjusted for all other independent variables, regardless of order. Hence, as table 4 displays that at significance level 5% [15], there is sufficient evidence to conclude that the main factors including (D/L) ratio (p-value 0.000 <0.05) affect the stress. However, cutout type has a different effect on stress since p-value 0.285 >0.05. The result of this study shows output that (D/L) ratio has an effect on the values of stress.

Table 4. Analysis of variance

Variable	Df	Adj SS	Adj MS	F-Value	p-value
Cutout type	3	932	310.7	1.35	0.285
(D/L) ratio	8	11884.6	1485.6	6.45	0.0000*
Error	21	4835.3	230.3		
Total	32	17745.1			

The procedure for selecting a model of which will indicate which variable or variables help explain stress begins by simply running the full model with all of the original variables. Stepwise selection as well as best subsets will be utilized to help find a model. This study has defined assumptions underlie the traditional GLM: (1) linearity; (2) normality of the residuals; (3) equality of residual variances; and (4) fixed independent variables measured without error. The parameters are linear dependent and the data were analyzed according to traditional linear regression analysis. Moreover, the parameter estimates for the "Cutout" variable is -12.51 with standard deviation 2.960, as predicted in table 5 The test statistic is t = -0.848 whereas the variable (D/L) ratio is significant by the t tests. The squared multiple correlation R^2 is equal to 0.72. Examination of the residuals indicates no unusual patterns. The inclusion of the " variables explains 72% of the variability of the data, a significant improvement over the smaller models. Since the P-values for (D/L) ratio is highly significant, variable may be included in the mode.

Table 5. Regression analysis stress versus cutout type, (D/L) ratio calculated regression equation

Variable	coef	SE coef	T -value	P-value
intercept	-8.9.9	10.526	-0.846	0.40403
Cutout type	-12.51	2.960	-0.848	0.438
(D/L) ratio	52.512	13.626	3.854	0.00057*

Calculated regression equation is shown below:

Stress = -8.99- 2.51 * cutout type + 52.5* (D/L) ratio (1)

It can be noted that from regression equation (1), increases in cutout type regardless of predict lower stress levels better than chance which that mean cutout is associated with decreases in stress number. On the other hand, increases in ratio regardless of predict higher stress levels better than chance. As result that when the (D/L) ratio increases the stress increase. Likewise, contour plot which shows the relation between stress versus cutout type, (D/L) ratio. The cutout types (circular, square, longitudinal rectangular, and transverse rectangular) represented respectively as numbers (1, 2, 3, 4), as shown in 'Figure 10'. The stresses increase as (D/L) ratio increase, as demonstrated in 'Figure 10'. Furthermore, the 'Figure 10' shows that the maximum expected frailer occur at ratio between 0.8-0.9.

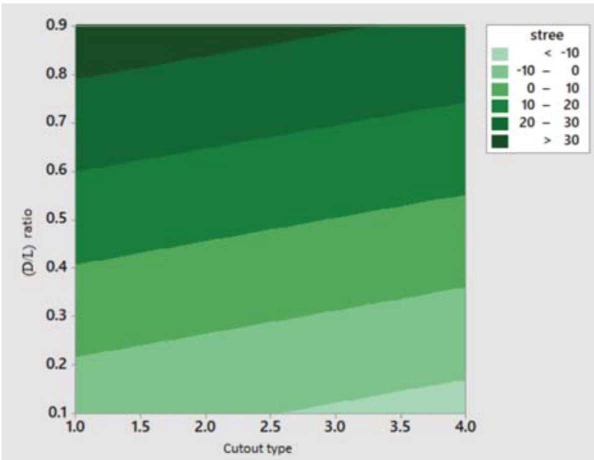


Figure 10. Contour plot

4. Conclusions

This study presents a validated finite element model of a fuselage. The finite element model results are correct and are consistent with the statistical results. The described method may also provide insights in describing stress distributions, and thus provide an opportunity for optimization of fuselage design. Both of the shape of cutout and (D/L) ratio have an effect on the values of stress and deflection. Therefore, for all of the cases consistently, the stresses increase as lamination angles increase. As a result, we can see that many differences occur in the maximum stresses, depending on the lamination angles. We demonstrate that the Regression statistical model is used to study the relationship between stress and other variables. This study investigates the link between stress outcomes and set of factors associated to cutout and ratio. For this purpose, regression model is implemented. This study indicates that the prediction of failure loads using regression is suitable for composite materials. It should be noted that stress the increases as ratio increases, as demonstrated. The maximum expected frailer occurs at ratio between 0.8-0.9

5. Acknowledgements
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