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Low-velocity Impact Analysis of Composite Repair Patches of Different Shapes

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LOW-VELOCITY IMPACT ANALYSIS OF COMPOSITE REPAIR PATCHES OF DIFFERENT SHAPES

A Thesis

Submitted to the Faculty

of

Embry-Riddle Aeronautical University

by

Sarvesh Baliga

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Aerospace Engineering

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Daytona Beach, Florida

LOW-VELOCITY IMPACT ANALYSIS OF COMPOSITE REPAIR PATCHES OF DIFFERENT SHAPES

by

Sarvesh Baliga

A Thesis prepared under the direction of the candidate's committee chairman, Dr. Sathya Gangadharan, Department of Mechanical Engineering, and has been approved by the members of the thesis committee. It was submitted to the School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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SYMBOLS

E	Modulus of elasticity
F	Force
G	Shear modulus
ν	Poisson’s ratio
ρ	Density
σ	Normal stress
σ_M	Mises stress
τ_{max}	Maximum shear stress
σ_1	Principal stress
V_f	Fraction by volume
Vm	Fraction by weight

ABBREVIATIONS

FEA	Finite Element Analysis
FEM	Finite Element Methods
CFRP	Carbon Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
FOD	Foreign Object Damage

ABSTRACT

The area under crack for various structures can be effectively repaired by the use of composite materials. Low velocity impact can cause barely visible damage to the interior structure of laminated composite. These impacts can cause delamination in composite materials. In this study, a Finite Element Analysis was conducted using Abaqus/Explicit and the results of the analysis were compared to the experimental data from literature. E-glass/epoxy composite laminate was subjected to a low velocity impact test. To study the effect of patch repair, a composite patch was applied on a cracked laminate and a low velocity impact was then conducted on this model. The FEA results were validated with the experimental data and an approach to model an ideal composite patch shape was conducted. Different patch shapes like square, rectangle, circle and ellipse were designed and analyzed on the crack by keeping the surface area of the patch common. All these patches were compared and an ideal patch shape was found for the model on the basis of stress concentration on the patch. Finally a parametric study was performed considering the change in impactor speed and impactor material on the impact damage. Thus, this research work readily demonstrates the effectiveness of finite element analysis of low velocity impact.

1. Introduction

1.1. Background and Motivation

High strength and high stiffness fiber-reinforced materials like glass/epoxy and carbon/epoxy are significantly used in the aerospace industry and material industry. They are highly flexible and have low elastic modulus. Due to low weight and low coefficient of thermal expansion these composite materials are used substantially. However, one of the biggest concern is that such structures are prone to impact loading while handling loads or when the loads are dropped. Serious damages may be caused by failure as a result of impact in composite structures in a variety of ways. It may cause delamination, matrix cracking or fiber breakage of the material. Low to moderate energies caused typically by impact forms delamination, cracking and fiber breakage. Penetration and shear damage at an excessive amount is caused by high impact energies (Abrate, 1998). The strength and stiffness of the damaged object, the stress state on the damage and the response of the damaged structure makes the problem complex.

It is a known fact that composite structures after impact can endure a major decrease in tensile strength and compressive strength (Sierakowski & Robert, 1997). To study and analyze the damage on a composite structure, several experiments have been conducted. Such experiments are conducted by replicating the real life situations in controlled environment. For instance, drop weight test is conducted to simulate the dropping of hard tools on composites. This test is generally low-velocity impact test. Damage because of low velocity impact on fiber reinforced composites is thought to be very risky for the most part, in light of the fact that the damage is not detectable to the exposed eye; this kind of damage is called as Barely Visible Impact Damage. A composite's compressive strength can undergo a loss of about 60% with this type of damage.

All in all, there are numerous parameters which characterize the way of the damage in composite structures, for example, delamination in composite structure, caused due to pressure loads. Different parameters which characterize the morphology of the impact incorporates impactor speed, geometric imperatives connected to the framework, impactor shape, and design of the affected structure. In this manner investigations of these parameters are critical in comprehension to the effect procedure and the damage brought on by them in the composite structures.

The damage caused by low velocity impact is inevitable. Hence, a repair or fortification of the damaged portion of the structure to restore the basic structural strength and efficiency is required. Applying composite patch repair is one of the latest solutions. Little research into the combined low-velocity impact damage resistance of the patch is available in published literature. The potential for an outwardly unnoticeable mix of the composite damage with likely adhesive damage recommends that low-velocity effect damage in composite repair is ought to be studied about and considered amid design configuration. It is costly and quite complex to conduct and perform physical experiments to evaluate impact damage on composite patches considering the quantity of distinctive parameters to be viewed and internal damages to be examined. Finite Element Analysis (FEA) gives a more financially savvy approach to foresee and survey damage in composite patches, and also giving a road to investigate numerous material mixes and designs. FEA can then show the areas where constrained trial testing may be important for acceptance of the damage behavior (Goodmiller, 2013)

Patch shape, properties of materials; thickness, orientation, and number of plies in the composite structure; quality of the bond surface, and damage tolerance properties of materials are some of the parameters that are important to feed in for the impact performance of the structure. The mechanics of the damage of the patch is also imperative to study the analysis of the patch performance. To have an appropriate and optimized patch design, it is important to understand the effects of input parameters, damage mechanics, and their interactions.

The aim of this research was to conduct a FEA which studied the damage mechanisms related to a composite patch performance on E-glass/epoxy material under low-velocity impact loading. The results from this analysis and simulation was compared to available experimental data in quantitative terms of stress, energy, displacement and contact force. Abaqus 6.13 was used for this research, which provided modules for composite structures and adhesive properties. Composite patch performance has limited availability of experimental data. Due to that and also because of a few obscure properties of materials needed for damage models, several assumptions were made. These includes assumptions of material strength, adhesive thickness and its properties. In addition to analysis of the patch, the parameters were studied to obtain an optimum composite patch shape for impact damage resistance based upon the stress carrying capacity. Other potential factors such as number of plies and its orientation, patch size, adhesive type, and thermal expansion mismatch were not examined in this study, but should be investigated in future work.

1.2. Overview

The significance of glass fiber reinforced polymer fiber (GFRP) has been, by and large perceived both in space and common flying commercial aircrafts and GFRP composite laminates are broadly utilized in many areas. Unfortunately, GFRP plies are excessively fragile when it undergoes dynamic loading, especially impact loading. In this way, the impact issues of composites have gotten to be critical. A dropped tool, bird strike or debris on the runway can produce delaminated zones due of foreign object damage (FOD), by impacts that are every now and again hard to distinguish with naked eye. Despite the fact that this damage may appear to be harmless to the composite structure, it may bring about untimely disastrous consequences by decreasing the strength of the material caused by the impact loading (Abrate, 1998). Due to distinctive types of damage it is quite evident that composite materials are very much prone to low-energy impacts. Delamination, for instance, is ordinarily seen between laminates of the composite material and, that under unique conditions, may be in a roundabout way capable for the last damage failure of a composite. The most extreme reason for composite delamination is low energy impact. The effects of such impact may result in significant reductions in strength and characteristics of damage tolerances. A complex distribution is followed by stress and deformation in the structure due to impact damage. For instance, matrix cracking is caused due to impact damage of low energies (where the velocity of impactor is less that 30m/s). Sometimes crack occur in the bottom of the structure because the laminate is flexible and it undergoes tensile flexural stress. A tensile crack is when a matrix crack in a structure is perpendicular to the laminate plane. Contact stresses causes the crack on the top of a structure for thick laminates. Such kind of cracks are known as shear cracks. The delamination between the adjacent plies occurs due to the matrix cracks. In this way there is an initiation of damage in the structure. So, in conclusion, when an impact takes place on a structure, it causes high stresses in the impacted area which in turn initiates cracks, propagates delamination and finally has a damage. Similarly damage start can be predicated by the presence of the first breaking of matrix, using a three dimensional stress analysis of the impact zone and proper damage failure criteria. At that point, delamination zones are determined and the proliferation of this delamination is concentrated on. The contact pressure causes stresses due to low velocity impact on these laminates. On the contact area when the contact force is integrated these stresses can be easily found. The impactor on the material has complex state of stress under it. Principal stresses ($\sigma_{1,}$ $\sigma 2$) and maximum shear stress (τmax) can be determined at each point to predict the failure in a laminate structure.

There are still no universally accepted analytical models where impact damage can be precisely predicted in the laminated composite due to their complex failure mechanism. There has been numerous studies on low energy impact damage. Hosur et al. (1998) studied the impact damage on composite laminates by analyzing the ultrasonic images. Luo et al. (1999) modeled and tested carbon/epoxy composite plates with a new method. Three different failure modes were considered in their research: matrix failure, interlaminar delamination and fiber breakage; conducted a simulation using the finite element software of Abaqus. However progressive failure of the structure were not considered in their studies. By considering the improved failure criterion Hosur et al. (1998) studied the impact damages in laminated composites. The strength and energy concept on the cross-ply laminate confirmed the failure mode. The relationship between transverse crack spacing and laminate strain were shown by these studies. To detect impact damage, experimental methods have also been suggested (Sierakowski & Robert, 1997). This involves the use of impact force as the principal parameter and defining the threshold for damage. Delamination is the major mode of failure for low velocity impact because there is a significant reduction in the compressive strength after impact and the level of energy needed to initiate delamination is low. Therefore a mathematical model is needed to simulate the change in material properties and also it is necessary to integrate the failure models provided into the load step/time step regime of a dynamic analysis. The nonlinear behavior of composite models can be precisely described by the integration of failure models.

1.3. Scope of thesis

The scope of this thesis consists of analytical study of low velocity impact analysis on a composite patch repair applied to a damaged composite plate using finite element method software Abaqus. The simulation results were verified with published results. Also, an investigation of the repair patch shape was conducted in order to obtain the ideal shape of the patch considering the stress carrying capacity. The simulation results of various parameters were compared with the published results in the literature. The damage analysis of the composite plate was performed using Hashin damage initiation criteria. The composite structure was modeled using eight-node quadrilateral elements.

2. Literature Review

2.1. Repair Patch Application

The technique of repairing a damaged structure with a fiber reinforced composite patch is turning out to be more far reaching among different engineering disciplines. Patches are as of now being utilized and researched for use as a part of application that ranges from airplanes and maritime vessels to bridges and building structures.

Composite repair solution is an alternative to conventional methods. Composite patch repair is a recent approach to repairing damage plates or any material structures. A composite laminate acts as a patch which is used to bond adhesively over a defected area in order to restore the load carrying capacity of the structure. The way it works is like a patch transfers loads around the defect and stops the defect from growing. The best part of it is that the composite patch can be applied directly on the cracked material without the use of hot work. This largely eliminates the fear of explosion hazard. In oil and gas industry this method is very much favorable. Here cold joining processes minimizes the impact of maintenance work or modifications due to the reduced danger of explosions. Some of the repairs may be used as a temporary solution until scheduled maintenance may be performed.

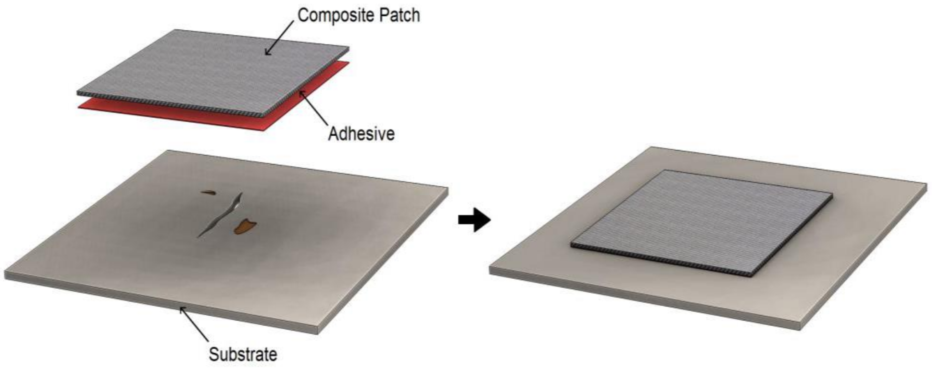


Figure 2. 1 Composite patch repair of a damaged area

2.1.1. Aerospace Industry Application

The aerospace industry spearheaded the utilization of reinforced composite patches for repair of metallic and other composite structures. Military aircrafts have been effectively repaired with composite patches for a considerable period of time, and the commercial airplane industry is starting to fuse the innovation too. Breakage in air ship structure commonly happen because of recurring fatigue loading at areas of stress concentration, for example, bolt gaps, regions of stress-corrosion, and material imperfections. The development of these breaks can have extreme effects on the lifespan of an air ship. Initially, secondary and tertiary structures were repaired using composite patch but lately primary structures are also being repaired. Residual stresses are considered very important when aerospace composite patches are concerned (Baker, 2003).

Following are a few instances of composite patch repairs in aerospace industry. Strain in the Royal Australian Airforce F-111 wing pivot was reduced by 30% with a boron/epoxy composite fitting as described by Chester (Chester, 2003). The acoustic failure of a composite bonded repair to the F/A-18 was investigated by Callinan and Galea, and they suggested that if a damping material was added it would significantly reduce the crack growth when compared to undamped or unpatched panels (Callinan & Galea, 2003). To restore the damaged airplane’s airworthiness during wars, Bartholomeusz et al. developed a fast repair technique with carbon/vinyl ester patches. It was proved by the experimental work that bonded composite damage repair were better than traditional fastened repairs considering all kinds of loading conditions (Bartholomeusz, Pearce & Vodicka, 2003).

2.1.2. Civil Engineering application

Civil engineers are starting to look at the utilization of composite repair patches for restoring failed and damaged structures. It was shown by Yollaway and Cadei (2002) that the primary area for the use of repair patches is bridges; corrosion caused by increasing use of de-icing salt and fatigue from traffic deteriorates the bridge structure. For such type of damaged structure, repairing and restoring is a viable alternative as compared to demolishing the structure. Yollaway and Cadei (2002) also provided the summary of all pertinent properties of the patch repairs for the bridges. Various works like I-704 Bridge, Newark, Delaware and the Bow Road Bridge in London were also mentioned by them.

There have been many researches on steel reinforcement in composite patches. To prepare cracked steel section, Colombi et al (2003) studied the use of pre-stressed composite patches. For strengthening of steel bridge girders with composite patches a set of guidelines were provided by Shaat et Al (2004). Durability, fatigue behavior, bond force and transfer mechanism, and galvanic corrosion of hybrid composite structures were also mentioned by Shaat in his research. Zhao et al (2007) researched about FRP and steel bonding and fatigue-crack propagation. Bocciarelli et al. and Colombi et al. both these researchers examined and studied fatigue performance of unconditioned, double-sided reinforcement under tension, which focused on stiffness degradation because of adhesive disbonding (Bocciarelli, 2009; Colombi & Fava, 2012). The current literature on strengthening steel structure with FRP composites was reviewed and studied by Teng et al (2012).

2.1.3. Naval application

Composite patches have their applications in naval and marine industry. On a Royal Australian Navy frigate a carbon fiber patch was installed. This installation was described by Grabovac and Whitetaker (2009). In order to restore the strength of the damaged structure these patches proved to be very important and effective. The patches were long lasting for about 15 years on a weather-deck.

Turton et al (2005) had done a lot of research on many marine structures for patch repair. He showed that in the case of Type 21 frigates, offshore drilling platforms, Type 42 destroyers and many more marine structures. For instance, composite patches were used on Type 21 frigates in the year 1981 in order to repair cracks. On testing it was found to be successful and so patch repairs were applied to all the other seven Type 21 frigates regardless if there were cracks or not. It was found that there were no other cracks in the ships after that and they were still at work as of last reported in the year 2005.

An offshore oil platform was repaired by composite patches due to the leaking of oil from the oil tank in Norway. Since the content being volatile, a welded repair was not an option because that would mean taking off all the oil and emptying it from all tanks of two bulkheads. The composite patch has low curing temperature, so only the oil from the affected tank had to be emptied to apply composite patch repair to it; this saved a lot of money and time (Turton & Dalzel, 2005).

A research on repair of underwater steel pipes was done by Shamsuddoha et al (2013). The research showed that composite patches can be used successfully on corroded pipes but it still requires more research before implementing it on a large scale basis.

2.2. Impact damage in composites

It is hard to predict the behavior of the impact damage of a material because it fails in multiple modes simultaneously. Matrix cracking, fiber-matrix crack, delamination and fiber fracture are some of the failure modes that are captured after cracking (Chandekar, Thatte & Kelkar, 2010). It is the properties of the composites that affect the impact behavior of the composite. Number of plies, thickness of the plies, material properties of the fiber and matrix and orientation of the ply are some of the properties of the composites that affect the impact behavior.

A sensitivity study was performed by Malik et al. (2013) on unstitched unidirectional composite materials. It showed that thickness and ply orientation had the largest effect on resisting damage by low-velocity impact. He also showed that longitudinal tensile strength was critical part of material properties. The size, mass, material and shape of the impactor also affects the damage (Hyung, Hong Sheng, & Chang, 1992)

The damage initiation and progress have been noted through many experiments and researches under low-velocity impact testing. The behavior of the impactor was noted by Belingardi and Vadori (2002). It was stated in his research that there are three outcomes of the impactor on impact, rebound, partial penetration and complete piercing. Lopes et al. (2009) in his research explained the process of impacting. He stated that when the impactor strikes the composite plate, its kinetic energy is initially transformed as elastic strain energy to the composite plate. There will be a point in the plate when an ultimate material strength is reached. When this takes place, permanent damage occurs as elastic strain energy is dissipated. When the velocity of the impactor reaches zero, all its kinetic energy by that time either gets converted to elastic strain energy or it is dissipated through damage. If the elastic strain energy is remaining, then the deformation of the plate and the impactor gets reversed and it gets accelerated in the opposite direction. This causes the strain energy converting back to kinetic energy which in turn causes the impactor to rebound after the strike. The plate gives out more energy after that as it continues to vibrate. If the elastic strain energy does not remain in the plate and is entirely dissipated by damage or vibration then the impactor gets penetrated in the plate. It will either remain in the same position in the plate or it will get pierced through the plate if there is any amount of kinetic energy left in it (Lopes et al., 2009).

A qualitative damage initiation and progress of the damage is described for Eglass/Epoxy composite with various configuration under low-velocity impact loading by Evci and Gulgec (2012). The first sudden drop of the load on the load-time curve causes beginning of impact damage. This occurs during the beginning of first delamination and it is called as Hertzian failure. The stiffness of the composite is significantly reduced after Hertzian failure. The magnitude of the force is depended on laminate thickness at the Hertzian failure point. This was observed by Shyr and Pan (2003). Maximum force is the second important point on the load-time curve which corresponds to the first intra-laminar failure. The force swing back and forth at this point until the maximum impact energy is reached (Evci & Gulgec, 2012).

The initial kinetic energy of the impactor is more than the energy dissipated by the impact, when low impact energies are concerned. This leads to rebound of the impactor. The compression in the top surface cause minor cracks in the matrix, while the fibers are strained at the bottom this also causes delamination in the bottom surface. Delamination also occurs in the interfaces between various plies inside the matrix. The delamination size is greater on the top and decreases as it goes to the bottom (Evci & Gulgec, 2012). The interlaminar stresses are highest between the layers with greatest ply orientation angle difference. This causes large delamination between the plies with greatest orientation difference between them (Lopes et al., 2009). The ply fiber orientation gives the direction and shape of delamination. Rebound of the impactor is caused by delamination (Siller & Bazant, 1983).

If the initial impact energy of the impactor is high then it may penetrate partially through the composite structure. If the penetration occurs, then the damaged area is approximately the size of the impactor diameter. The high stress by the impactor here causes matrix and fiber crushing and breakage of the area under the impactor (Evci & Gulgec, 2012). This can also cause a permanent scratch or indentation. A 1 mm size of indentation is considered as the limit for the damage to be called as “barely visible damage” (Lopes et al., 2009). When there is a matrix cracking, it goes downwards to 45°, which makes an undamaged cone shaped area under the impactor. Fiber breakage is formed under the undamaged cone area in the bottom (Siller & Bazant, 1983). The delamination is more in the case of penetration when compared to the case of rebound (Evci & Gulgec, 2012).

The impact energy is greater than the total possible dissipation energy and elastic energy both combined in the case of impact causing complete piercing of the impactor in the composite. When the impactor goes through the composite plate it gives out some energy through fragmentation of materials and its kinetic energy is maintained

(Belingardi & Vadori, 2002). In this fiber breakage takes place during the damage. The size of delamination is smaller as compared to the cases of rebound or partial penetration of the impactor (Evci & Gulgec, 2012). When it comes to complete piercing of the impactor it is more than the low-velocity impact, and so it is beyond the scope of this thesis research.

2.3. Theories and properties

2.3.1. Impact Dynamics

Considering the life of a structure impact from foreign objects is quite evident every now and then. It is more evident in manufacturing, service and maintenance operations. For instance, impacts occurs during take-off and landing of an aircraft. Workers drop their tools on the structure during maintenance services. Impact damage is small in this case. Most laminated composites undergo impact damage throughout their life. As read in the first Chapter such impact damages cannot be easily detected through naked eyes. Such damages cause decrease in strength, hence, appropriate care and measures should be taken in the process of designing. Therefore it is necessary to learn and understand the impact of damage by the foreign objects on composites.

2.3.2. Structures and Properties

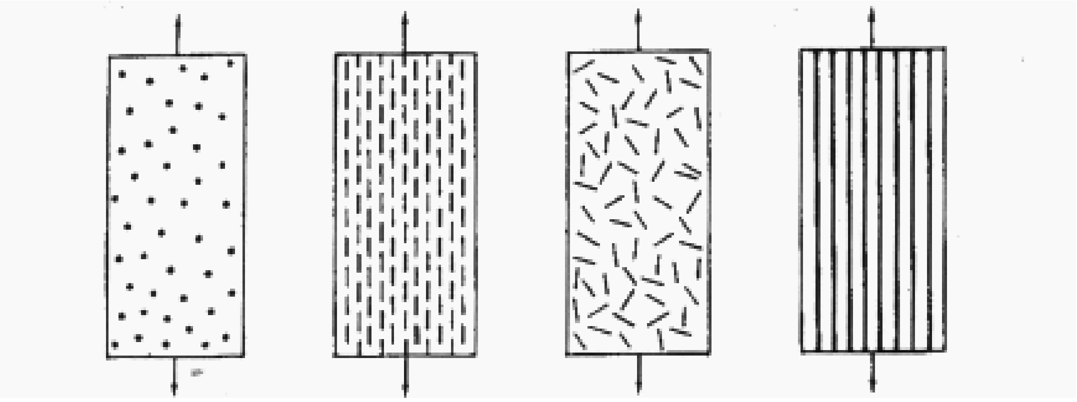
Composite materials are generally made by combining a matrix and reinforcement structures which has all the required and desirable properties and they are better than the constituent individual materials. Fiber reinforced polymer matrix composites are hugely used composites. For polymer composites, epoxy material are very highly used. Epoxy has extremely good properties. It acts as a very good adhesive, it has high strength, low shrinkage and it is a very fine anti-corrosive material. Reinforcement is the second part of the composite material. Fiber reinforcement is exclusively used most of the times. Fiber material gives the maximum strength to the composite that is the reinforcement part of the composite. The tensile strength of the fiber is very high so the matrix contributes towards the strength of the composite in longitudinal and compressive direction. Reinforcements can be of various types; short fibers, long fiber and particles are some of the examples.

When composites are compared to monolithic materials, their strength and stiffness may be either less or equal to them like for instance when compared to metals. But when specific stiffness (stiffness to weight ratio) or specific strength (strength to weight ratio) are taken into consideration, composites are far better than metals.

2.3.3. Classification of Composites

Since the properties of the composites vary a lot in different directions and the reinforcements are distributed in a variety of ways, so composite material shows anisotropy in them. The channel between the fiber and the matrix is very critical since the load is transferred through this channel. This channel plays a very crucial role in determining the composite properties. When composite materials are classified according to their matrix they are; metal matrix composites, polymer matrix composites and ceramic matrix composites.

Another method of classifying composites is based upon the type of reinforcement pattern. They are; (a) Particulate random, (b) Discontinuous aligned, (c) Discontinuous random, and (d) Continuous aligned



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

Figure 2. 2 Arrangement and types of reinforcements

The most common form of reinforcement used is fiber. Generally most of the materials are stronger and stiffer in fibrous form as compared to any other form. Fibers have high stiffness and low density. Glass fiber, carbon fiber and boron fiber are the most common types of fiber materials used in composites. Comparison of various fibers is shown in figure 2.2.

Metals, polymer and ceramics are generally the matrix materials. However, polymer matrix are used on a wide scale for variety of purposes as compared to other matrix materials. Polymer matrix can be categorized into thermoplastics and thermosets. Also epoxies are of two kinds, ones that can be cured at low temperature and the others that can be cured at high temperatures.

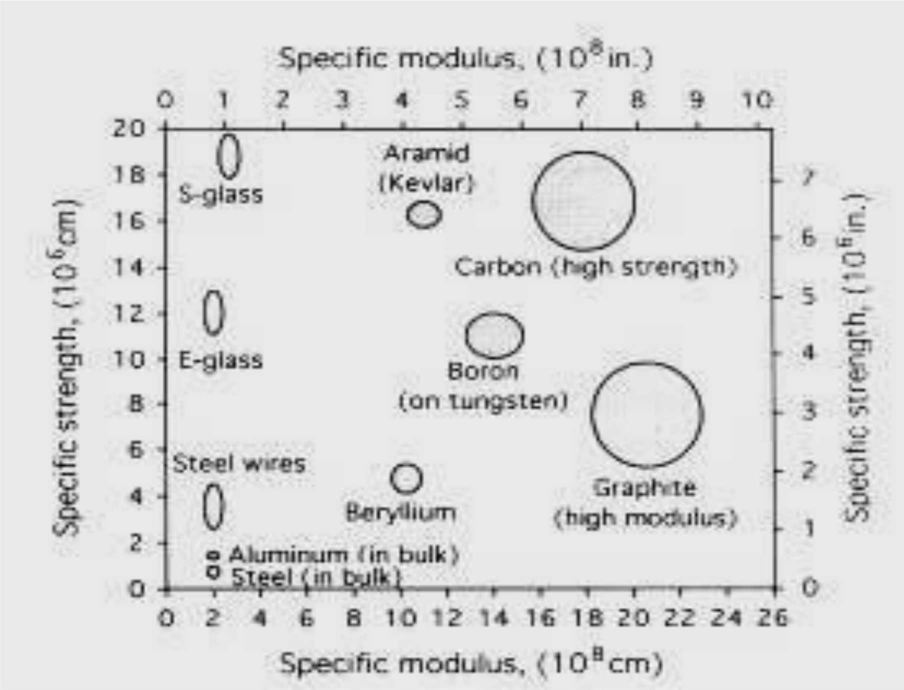


Figure 2. 3 Mechanical properties of different fiber

Since, composite materials have various constituents, they have various characteristics. Specific strength and specific modulus of a composite affects the quality of performance of the composite. Glass/epoxy has its highest specific modulus and strength when it is in its unidirectional form. The fiber in the composite affects the unidirectional composite’s behavior in the fiber direction, which is generally the stiffness. The matrix controls the behavior in transverse direction which is mostly the strength.

Since there is no contribution of fibers towards the strength in transverse direction, also considering that the strength of the matrix is low, it becomes essential to place the fibers in different directions in order to undergo the loads of any amount. The preferable angle of orientations of lamina are 0°, 45°, -45°, and 90°. The axial load is carried by the lamina with 0° degree angle, 45° and -45° angled plies carry shear loads and the lamina with 90° carry the load in transverse direction.

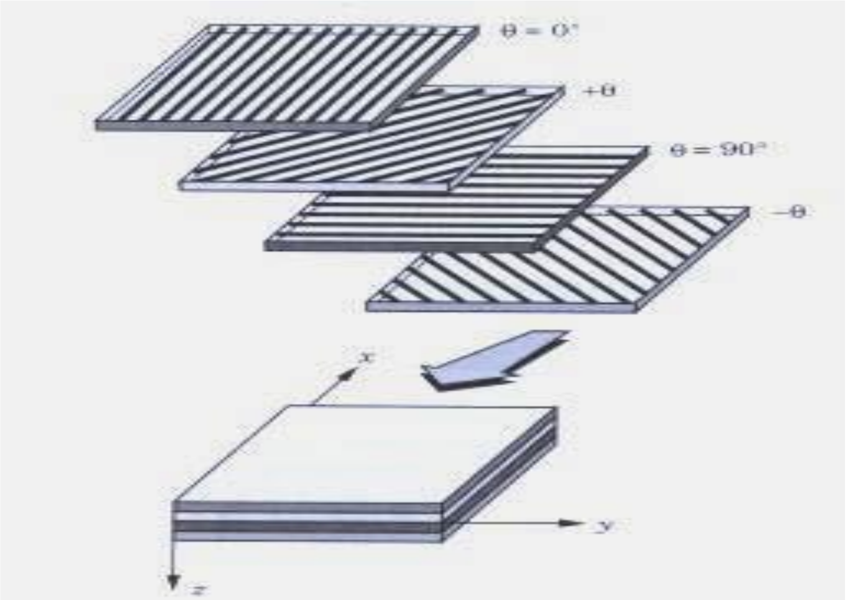


Figure 2. 4 Lamination sequence

Table 2. 1 Constitutive properties of composite materials

Property	**Carbon/Epoxy** **(AS4/3501-6)**	**Graphite/Epoxy** **(GY-70/934)**	**EGlass/Epoxy**
Fiber Volume ratio, V_f	0.63	0.57	0.55
Density (σ) g/cm^3	1.58	1.59	2.1
Longitudinal modulus (E_1) GPa	142	294	39
Transverse tensile strength (F_{2t}) GPa	10.3	6.4	8.6
In-pane shear modulus (G_{12}) GPa	7.2	4.9	3.8
Longitudinal tensile strength	2280	589	1080

Property	**Carbon/Epoxy** **(AS4/3501-6)**	**Graphite/Epoxy** **(GY-70/934)**	**EGlass/Epoxy**
(F_{1t}) GPa			
Transverse tensile strength (F_{2t}) GPa	57	29.4	39
In-plane shear strength (F_6) MPa	71	49.1	89
Longitudinal compressive strength (F_{1e}) GPa	1440	491	620
Transverse compressive strength (F_{2c}) GPa	228	98.1	128

2.4. Properties of Composites based on Micromechanics

Micromechanics helps to predict a few basic properties of a composite material. These properties of the composite structure are based upon the amount of matrix and reinforcement. The amount of reinforcement and matrix are calculated by its weight fraction (w) or volume fraction (v). The equation of weight fraction and volume fraction is given as:

$$w_f + w_m = 1 \qquad (2.1)$$

$$v_f + v_m = 1 \qquad (2.2)$$

Where f and m are denoted by fiber and matrix respectively.

2.5. Analytical Work

Park et al. conducted a study on impact damage analysis and test of composite laminate for aircraft repairable design. This study focused on low velocity impact damage evaluation and patch repair of carbon/epoxy unidirectional and fabric laminate. Both these tests were simulated using drop weight test equipment. The damaged part was repaired using external patch repair method by removing the damaged area. This was also simulated by finite element analysis and the results were compared.

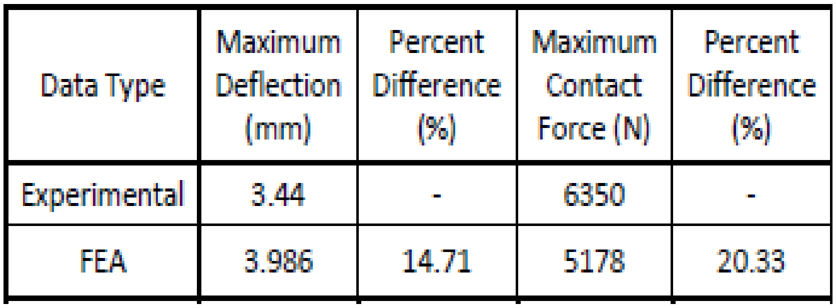
A composite panel of 100 mm x 150 mm was used in this test. The layup sequence for unidirectional laminate was $[45°/0°/-45°/90°]_{4s.}$ The layup sequence for fabric laminate was $[(45°/-45°)/ (0°/90°)]_{5s}$. The dimension of the patch was 23 mm x 23 mm having 4 plies in it. The finite element analysis was performed using MSC Nastran solver and the results were obtained in the form of stresses. Total number of elements for FEM mesh generation were 3677. The following figure shows the comparison of FEM analysis and test results.

Table 2. 2 Comparison of Results

	UD Laminate		**Fabric Laminate**	
Stress (MPa)	**Test**	**FEM Analysis**	**Test**	**FEM Analysis**
	84.7	97.8	131.8	139

Geoffrey (2013) conducted an investigation of composite performance under low-velocity impact loading. Here the experimental setup consisted of a 60 mm x 60 mm hybrid plate, struck by a 20 mm DIA, 1.91 kg hemispherical impactor at 3.5 m/s. Four plies, arranged quasi-axially as [0/-45/90/45] with a fiber volume fraction of 30%, composed the 2.3 mm thick E-glass/polyester composite layer. This was attached to a 0.5 mm thick SUS304 stainless steel sheet. The finite element analysis was performed in Abaqus and the FEA results were compared to the experimental results.

The following table compares the percent differences between the FEA results and the experimental data. Good agreement was found between the FEA results and experimental test data.



Data Type	Maximum Deflection (mm)	Percent Difference (%)	Maximum Contact Force (N)	Percent Difference (%)
Experimental	3.44	-	6350	-
FEA	3.986	14.71	5178	20.33

Figure 2. 5 Comparison of FEA results and experimental data

3. Experimental Setup

Geofrey et al. (2010) conducted low velocity impact experimentally. Experimental data from this study was used as reference for FEA analysis in this research. Geofrey et al. conducted a drop weight test to simulate low velocity impact on an E-glass/epoxy composite laminate. The experimental setup had nine layers of E-glass/epoxy laminates with alternating 0° and 90° plies. The dimension of the laminate was 100 mm x 100 mm and its total thickness was 4.04 mm. This plate was subjected to an impact of 20 J under the velocity of 4.472 m/s. E glass fabric, type C of IS: 11273 were used to fabricate composite laminates. An epoxy matrix based on Lapox L-12 resin and K-5 hardener was selected for making composite panels.

In the next step of the experiment, a cracked laminate was applied a composite patch upon it. The crack was deep up to the third layer of the composite ply while the crack dimensions were varied. The crack dimension for the first case was 5 mm x 5 mm and for the second case it was 5 mm x 7.5 mm. This composite patch had an orientation of 90°. The dimension of the patch used was 10 mm x 10 mm and the thickness of the patch was 1 mm.

4. Modelling and Analysis

4.1. Development of Finite Element Model

Finite element method is a numerical technique that is used to find solutions to a large level and variety of engineering problems which includes stress analysis in dynamic conditions. The three basic steps to perform finite element analysis are, pre-processing, solving and post-processing. In pre-processing, geometric models are made as per the requirement. The modeled geometry is then applied with appropriate meshing. Material properties are assigned to the elements and boundary constraints are applied to the nodes of the element. The next step involves, solving which is the processing of geometric data. After the data is processed the output file is generated. The third step is post-processing which involves studying the obtained data in the form of stress, strain and force graphs. In this research Abaqus serves as both, pre-processor and post-processor. Abaqus is an interactive 3D modeling software that can be used to model many complex and simple components in engineering. Since, it has very user friendly tool interface and extensive customizing capacity, it is used on a large scale for modeling. Solving and post-processing both the jobs are done in this software. Abaqus software has explicit and implicit finite element program that is used to analyze the responses that are non-linear and dynamic. It has a fully automatic definition of contact areas and a large library of constitutive material models and failure models.

A finite element model of a symmetric, cross ply, laminated composite and impactor were modeled in Abaqus design module. The finite element model consisted of nine separate layers with each layer being 0.44 mm thick and 100 mm x 100 mm in dimension. The orientation of these layers was [0/90/0/90/0/90/0/90/0]. Every layer were attached to each other with a cohesive layer between them having a thickness of 0.1 mm. The total thickness of the composite structure was 4.04 mm. These plies were modeled with SC8R: 8 node, quadrilateral, reduced integration, continuum shell element. It had enhanced hourglass control with Hashin damage viscous stabilization factor of 1 x $10^{-7.}$

The material that was modelled was E-glass/epoxy. The material properties of the E-glass/epoxy used in this test is shown in the figure 4.1.

Table 4. 1 Material properties of E-glass/epoxy lamina

Property	**Units**	**Value**
ρ	g/cc	1.8
E_1	GPa	45.6
E_2	GPa	16.2
E_3	GPa	16.2
ν_{12}	-	0.278
ν_{13}	-	0.278
ν_{23}	-	0.4
G_{12}	GPa	5.83
G_{13}	GPa	5.83
G_{23}	GPa	4.5
X_t	Mpa	1280

Property	Units	Value
X_c	Mpa	800
Y_t	Mpa	40
Y_c	Mpa	145
S_L	Mpa	73
S_T	Mpa	54.8
ε_{1t}	%	2.807
ε_{1c}	%	1.754
ε_{2t}	%	0.246
ε_{2c}	%	1.2
G_f^t	N/mm	17.965
G_f^c	N/mm	7.016
G_m^t	N/mm	0.049
G_m^c	N/mm	0.87

Elements are 0.5 mm x 0.5 mm in the center of the mesh and their size increases with the distance from the impact zone. The adhesive layer between every ply is of 0.1 mm thick and it properties are given in the figure 4.2.

Table 4. 2 Material properties of adhesive

Property	Units	Value
ρ	g/cc	1.9
E_1	GPa	1.85
ν_{12}	-	0.33
G_{12}	GPa	0.487
$\sigma_{tf} = T_o$	MPa	21.63
ε_f	%	4.77
$\tau_f = S_o$	Mpa	17.9
γ_f	%	43.9
G_{1c}	N/mm	0.43
G_{11c}	N/mm	2.1

Maximum degradation for these elements was set at 99% and linear bulk viscosity was set at 0 as suggested in the Abaqus user manual. Using surface to surface tie tool in Abaqus, these layers are tied together.

An impactor was modeled, providing impact energy of 20 J and velocity of 4.472 m/s. A friction penalty of 0.5 was provided for the contact between the impactor and the composite layer.

The impact simulation was run in Abaqus/Explicit, with a time span of 0.001 seconds. The linear bulk viscosity parameter was set at the recommended value of 0.06, and the quadratic bulk viscosity parameter was the recommended value of 1.2.

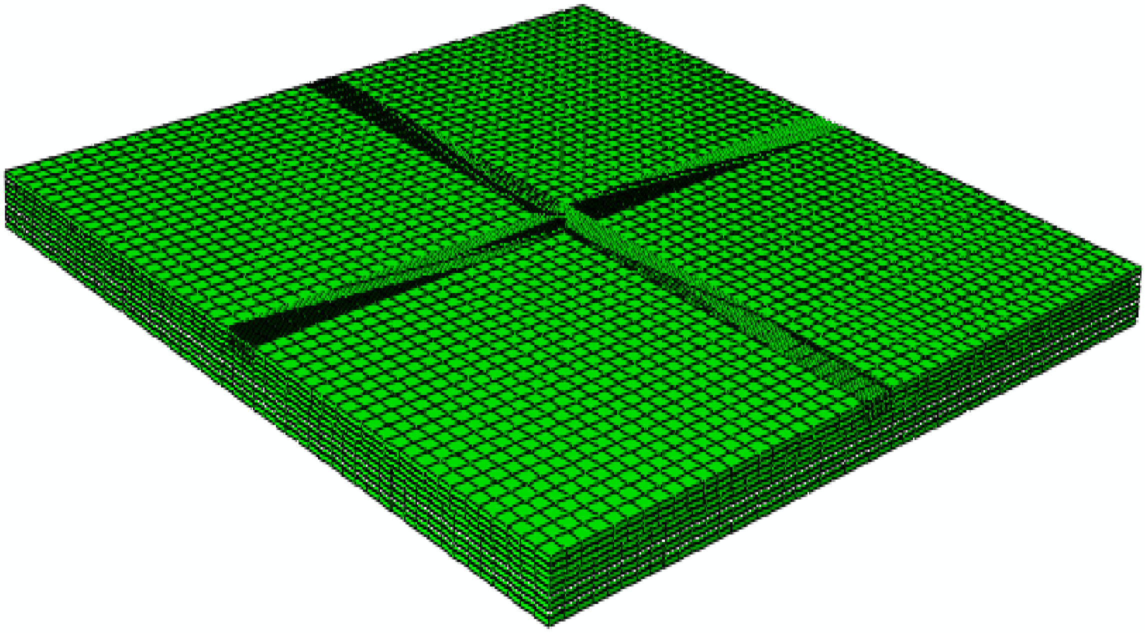


Figure 4. 1 Modeling of the composite laminate

The second part of the test involved creating crack in the composite layer and a patch for the crack. This involved two tests with crack of thickness 1.34 mm and varying thickness. The first composite was modeled with 5 mm x 5 mm crack dimension and the second composite was modeled with 7.5 mm x 5 mm crack dimension. A patch was modeled for both the conditions. This patch was made of the same E-glass/epoxy element with a single layer having orientation of 90°. The thickness of this patch was modeled to 1 mm and other dimensions were 10 mm x 10 mm. The patch was attached to the composite using the cohesive layer.

Both these models were validated comparing with the experimental results and the shape of the patch was changed as per the stress concentration so as to provide with an ideal shape.

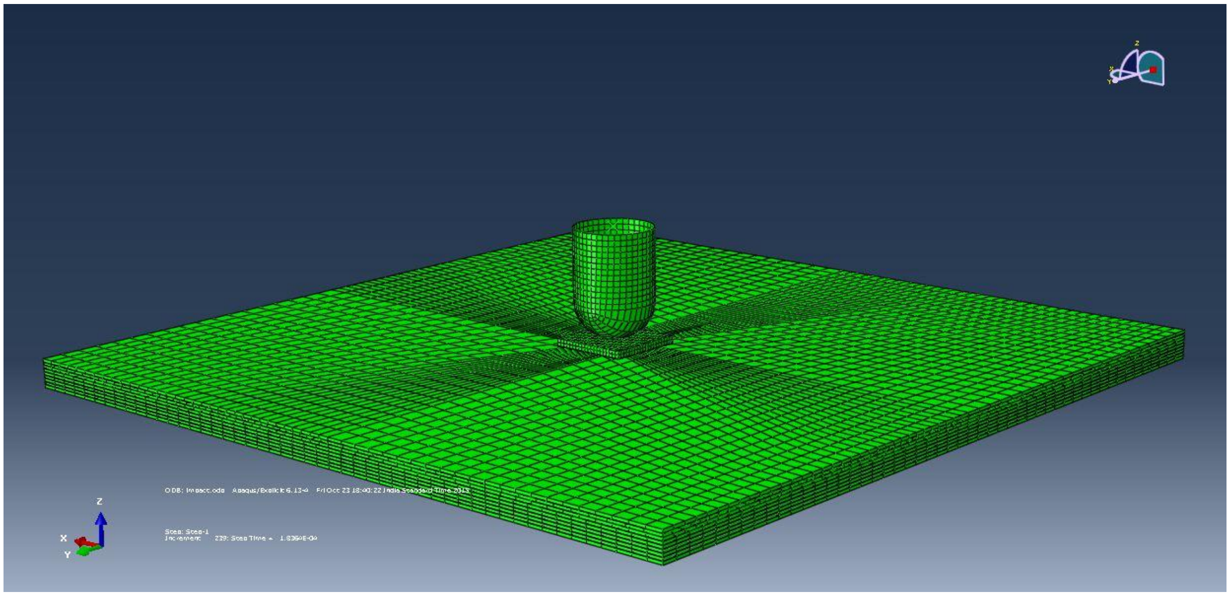
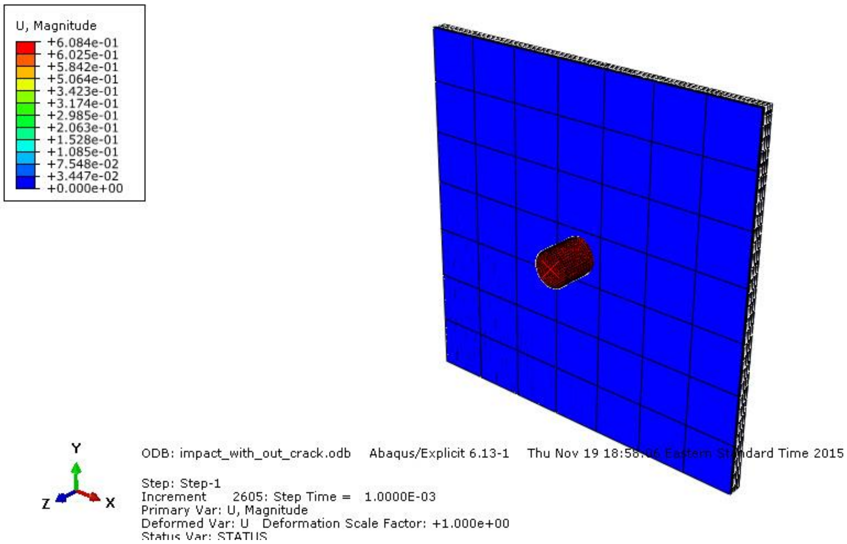


Figure 4. 2 Modeling of the composite patch and impactor

4.2. Sensitivity Study

In order to have a proper approach for analysis, it is required to have an appropriate mesh. So, a sensitivity study was performed to obtain a good mesh. Meshes that are good enough are ones that produce results with an acceptable level of accuracy, assuming that all other inputs to the model are accurate. Mesh density is a significant metric used to control accuracy (element type and shape also affect accuracy). Assuming no singularities are present, a high-density mesh will produce results with high accuracy. However, if a mesh is too dense, it will require a large amount of computer memory and long run times, especially for multiple-iteration runs that are typical of nonlinear and transient analysis. One of the ways to evaluate the quality of the mesh (and a model overall) is to compare results to test data or to theoretical values. Another way is to refine the mesh until a critical result, of a parameter converges (i.e. it doesn't change significantly with each refinement).



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ODB: impact_with_out_crack.odb    Abaqus/Explicit 6.13-1    Thu Nov 19 18:58:06 Eastern Standard Time 2015

Step: Step-1
Increment      2605: Step Time =   1.0000E-03
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +1.000e+00
Status Var: STATUS
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Figure 4. 3 Displacement for 44149-elements model

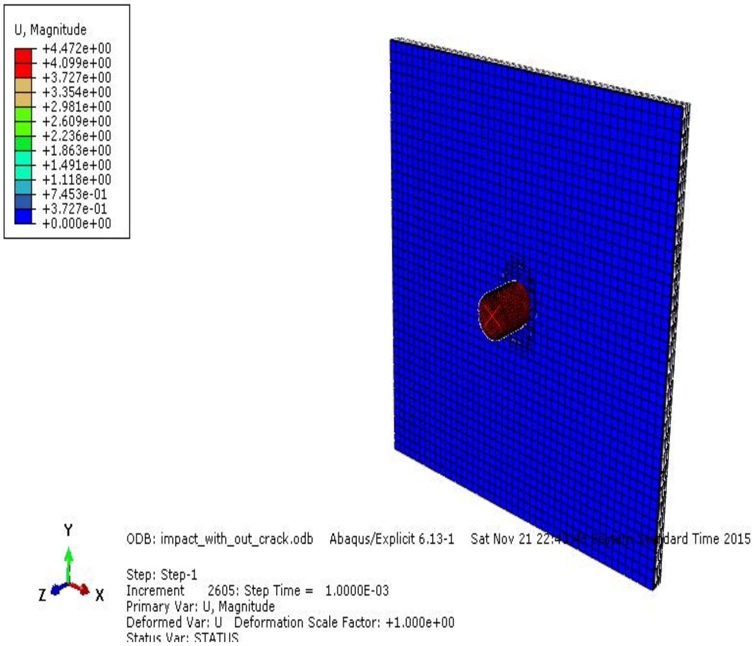

Figure 4. 4 Displacement for 49284-elements model

The above figures show the comparison of displacement based on fine mesh and coarse mesh size.

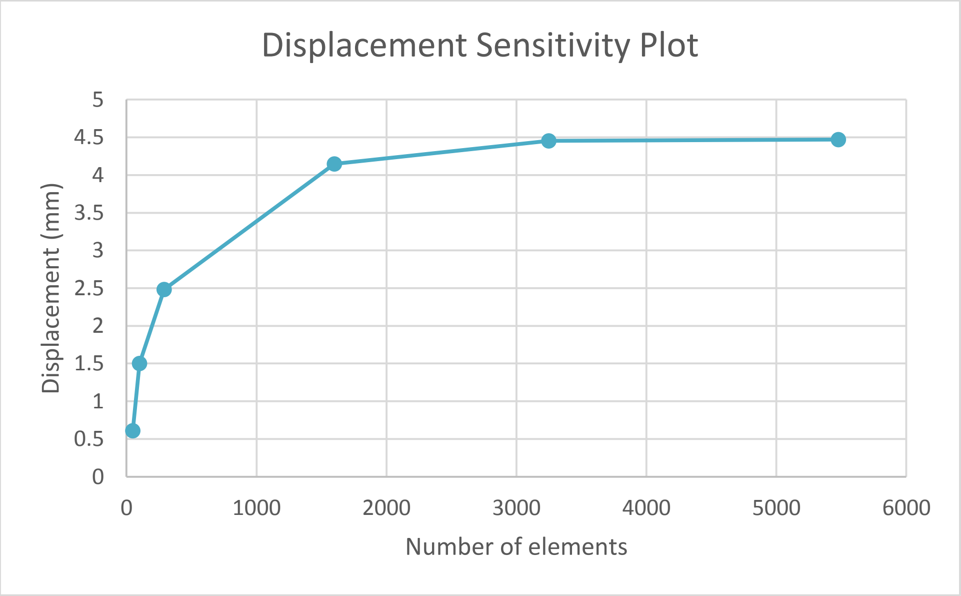

Figure 4. 5 Displacement sensitivity plot

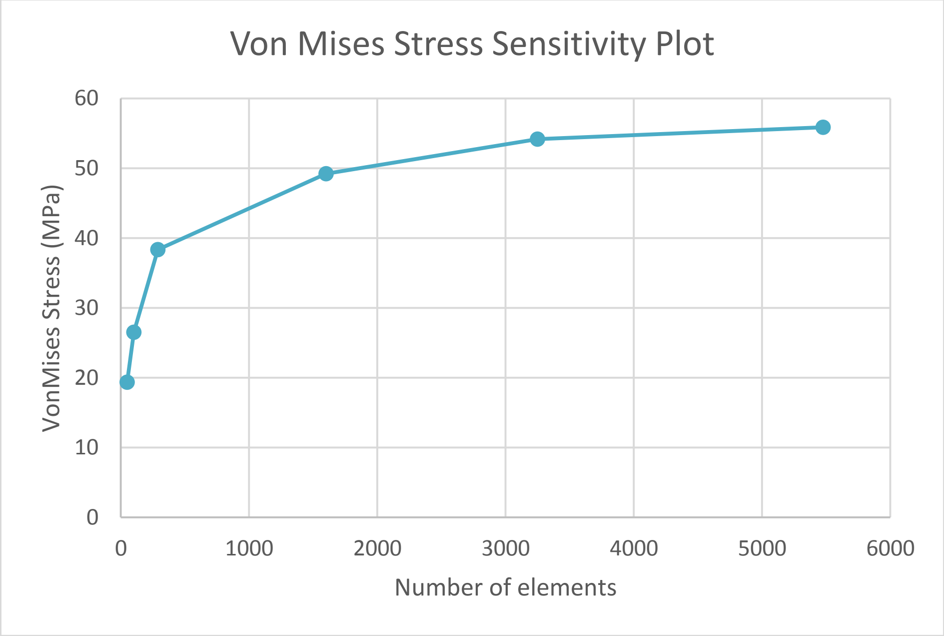

Figure 4. 6 Von-Mises stress sensitivity plot

Figure 4.7 is the plot between displacement and number of elements and figure 4.8 is a plot between Von-Mises stress and number of elements. It can be observed from the plots that the graph of displacement and Von-Mises stress converges when the number of elements are 49284.

4.3. Validation Results

A comparison of experimental results and finite element analysis was done. Both the results showed a good agreement in between the two.

Following table shows a comparison of stress, contact force and displacement obtained in both the analysis.

Table 4. 3 Comparison of result for composite laminate

Parameter	**Contact Force**	**Maximum Displacement**	**Von Mises Stress**
Experimental	5170.4 N	6.283 mm	54.98 MPa
FEA	5468 N	4.472 mm	55.88 MPa
% Difference	5.44	28.82	5.43

The above results were a comparison for nine layer composite laminate without the patch. The experimental tests conducted with the patch also showed good accordance with the finite element test results.

Following is the comparison of both the approaches for 5 mm x 5 mm crack on the composite.

Table 4. 4 Comparison of result for the first patch

Parameter	**Contact Force**	**Maximum Displacement**	**Von Mises Stress**
Experimental	1097 N	1.42 mm	78.53 MPa
FEA	1579 N	1.20 mm	75.95 MPa
% Difference	30.52	15.49	3.28

Other laminate had a crack of 5 mm x 7.5 mm. The results of these laminates are as shown below.

Table 4. 5 Comparison of result for the second patch

Parameter	**Contact Force**	**Maximum Displacement**	**Von Mises Stress**
Experimental	3732 N	0.79 mm	38.42 MPa
FEA	4294 N	0.689 mm	37.75 MPa
% Difference	13.08	12.78	1.74

5. Towards Ideal Repair Patch Shape

After the validation of models used in the experimental tests were completed, a need for an ideal repair patch was required. Though the finite element analysis results were very much in agreement with the experimental results, it is still not certain that the shape of the patch used is the ideal one. The patch shape matters a lot when it comes to repairing of the material. The amount of stress concentration changes with the change of shape of any material. For instance, a shape with more cornered edges may have higher stress concentration when compared to the ones with lesser or no edges. This is good enough to know that the patch shape used in the experimental test may not be an ideal one.

To have a better patch shape for the crack, different shapes of nearly same areas were modeled and analyzed. The experimental test which was taken into consideration was the one with the crack length of 5 mm x 7.5 mm. As shown above the square patch of 10 mm x 10 mm with a thickness of 1 mm was already conducted, this research modeled and analyzed the patch having rectangle, circle and ellipse shapes. In order to have a fair comparison between the shapes, all the shapes were designed such that each of these had more or less the same surface area.

The rectangular patch that was used had dimensions 15 mm x 6.7 mm. The thickness of this patch was kept the same as 1 mm.

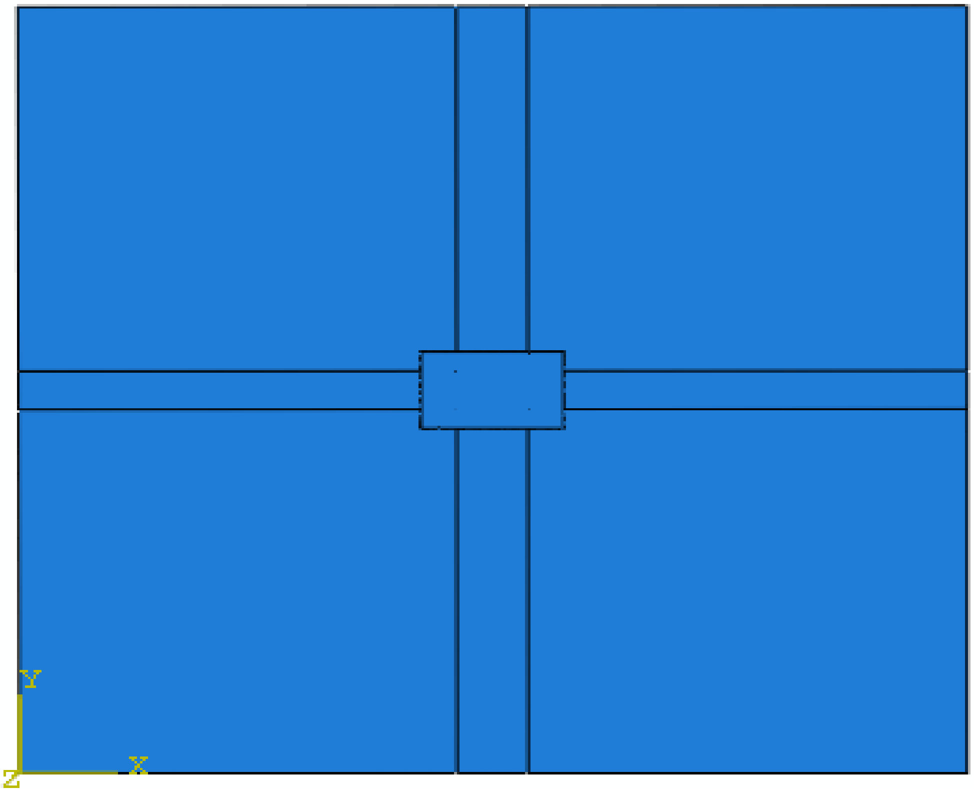

Figure 5. 1 Rectangular patch model

The next repair patch model that was designed was the circular shape. For the circular patch shape the dimension was taken as 5.65 mm radius. This dimension was taken into consideration, in order to maintain the uniformity in the surface area of the patch. The surface area of the circular patch was approximately 100 sq.mm.

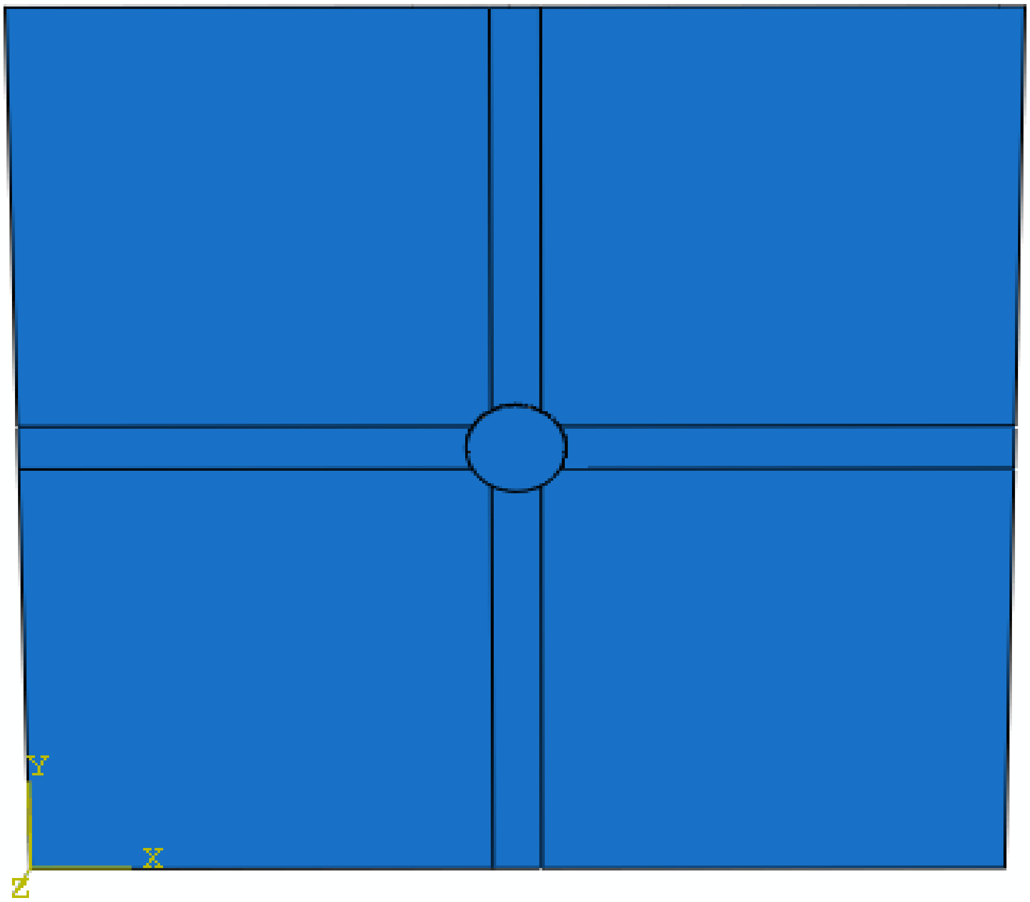

Figure 5. 2 Circular patch model

The shape of the next patch that was considered was ellipse. Since, the area of the ellipse should be the same as that of the other composite patches, to define this similarity, the dimension of the ellipse was taken carefully into consideration. The major axis of the ellipse was taken as 15 mm and the minor axis was taken as 8.5 mm. In this manner when it’s surface area was calculated it gave the value approximately around 100 sq.mm.

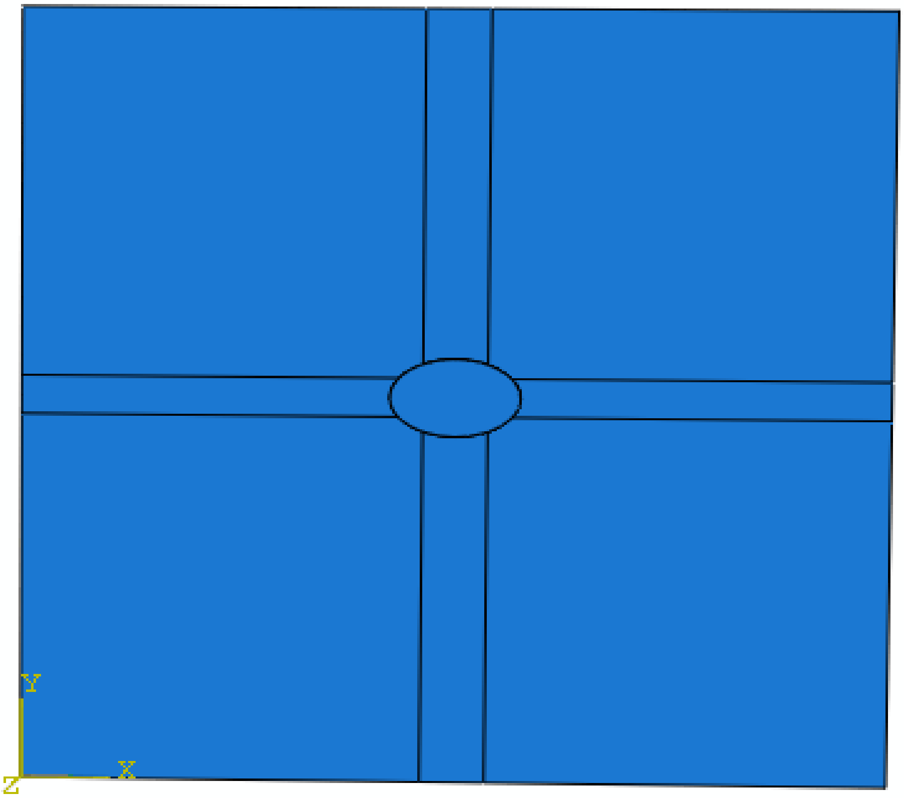

Figure 5. 3 Elliptical patch model

Table 5. 1 Areas of different patch shapes approximately equal to 100 sq mm

Shapes	**Area Formula**	**Area (sq mm)**
Square	Length x Breadth	100
Rectangle	Length x Breath	100.5
Circle	π x (Radius) ^{2}	100.1
Ellipse	$\pi \times \frac{Major\ axis}{2} \times \frac{Minor\ axis}{2}$	100.2

6. Results and Discussion

6.1. Rectangle Patch

Around the crack tip, a rectangular mesh pattern was created. Around the rectangular pattern another rectangular area was created. The displacement on the rectangular patch shape after analysis was found to be 0.448 mm. Fig 6.1 shows the Von Mises stress from the analysis.

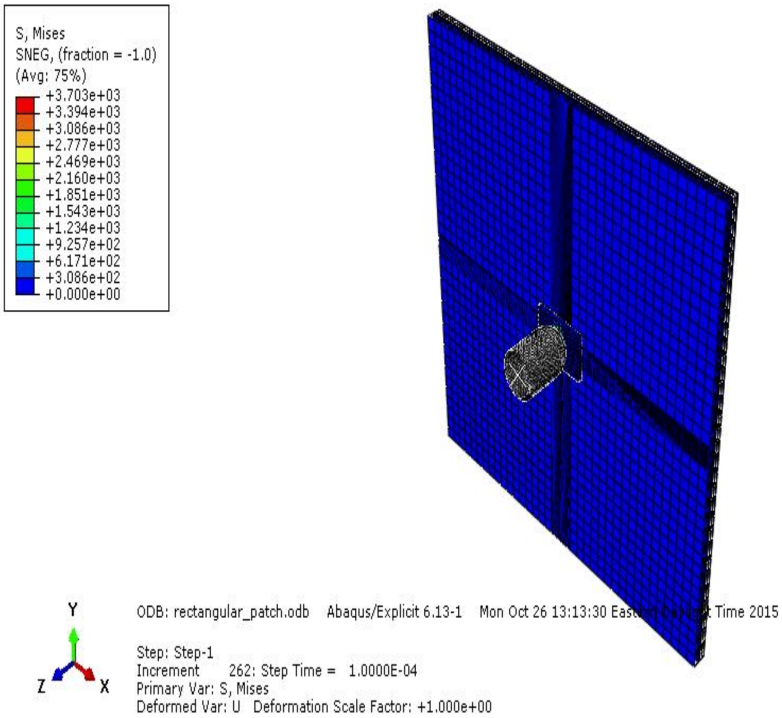

Figure 6. 1 Von Mises stress for rectangular patch

6.2. Circular Patch

A circular patch was placed on the crack surface. The displacement in the patch was found to be 0.42 mm. The Von Mises stress on the circular patch is as shown in figure 6.2. The displacement in this patch was found to be 0.4472 mm.

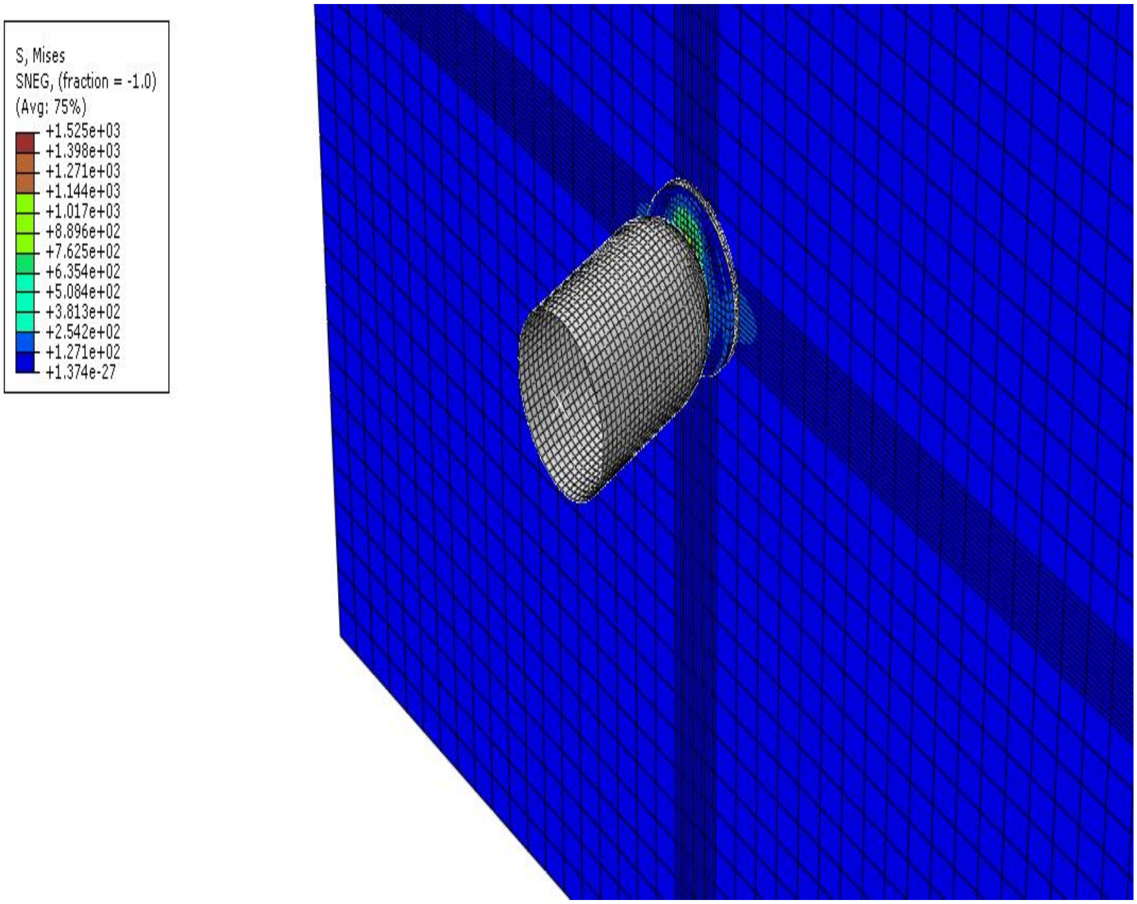

Figure 6. 2 Von Mises stress for circular patch

6.3. Elliptical Patch

Elliptical patch was the last patch that was modelled in the test.

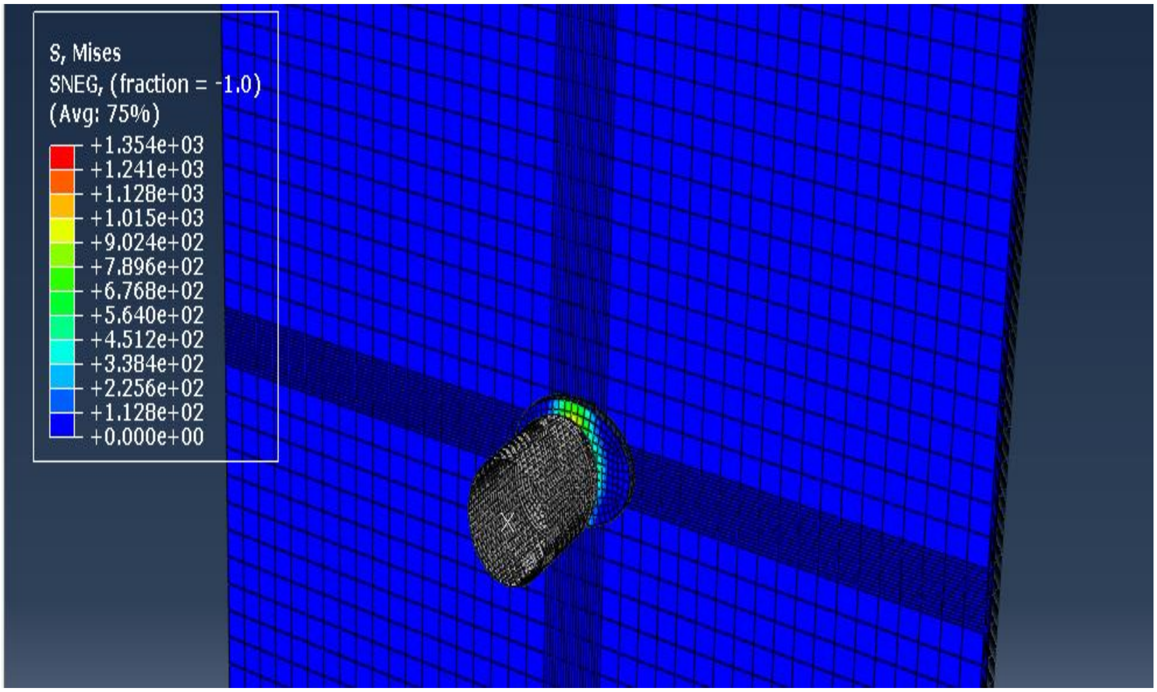

Figure 6. 3 Von Mises stress for elliptical patch

The maximum displacement obtained after analysis in these patches is given in Table 6.1.

Table 6. 1 Maximum displacement comparison

Patch Shape	**Maximum Displacement (mm)**
Square	0.689
Rectangle	0.448
Circle	0.447
Ellipse	0.447

It is shown in Table 6.1 that the maximum displacement is more in the square patch. The maximum displacement decreases for the remaining patches. The maximum displacement is more or less equal for rectangle, circle an elliptical patches.

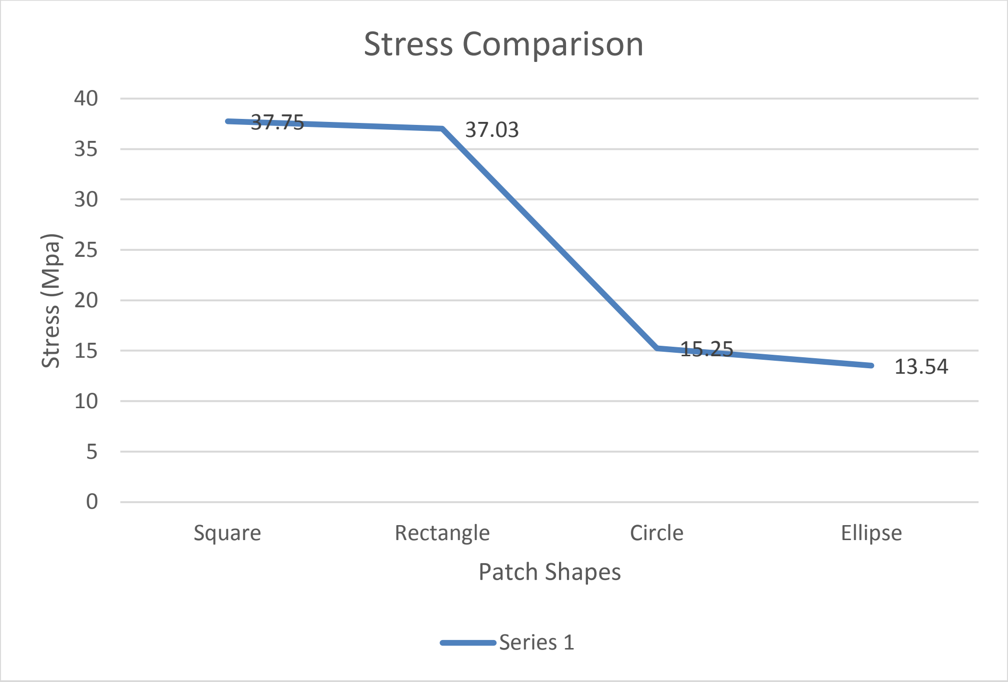

Figure 6. 4 Stress comparison

Figure 6.4 shows the Von Mises stress concentrated on various patch shapes. The Square patch has the highest stress concentrated which comes to 37.75 MPa. The rectangular patch has stress lower than square patch which is 37.03 MPa. The circular and elliptical patch has stress far lower than the quadrilateral. The circular patch has stress concentration of 13.92 MPa. Elliptical patch shape has the lowest stress of all the patch shapes which is 13.54 MPa.

7. Parametric Study

Once the Finite element analysis was completed a parametric study was done to understand the effect of uncertain inputs with existing boundary conditions and geometry. Impactor material and impactor velocity are the two topics included in this parametric study. For all the simulations the thickness of the composite was kept constant throughout the process.

Steel and aluminum projectile were used for parametric study of impactor material. The impactor diameter and velocity were kept the same as that used in the tests. This study was specifically to see the effect of changing material of the impactor on the impact damage. There were differences observed in the impact force with the change in materials. Having the same impact velocity, aluminum and steel had the kinetic energy in a similar ratio. The maximum impact force of steel was found to be 1000.5 N and that of aluminum was 912 N. Figure 7.1 shows a plot of impact force vs time for both aluminum and steel impactor materials.

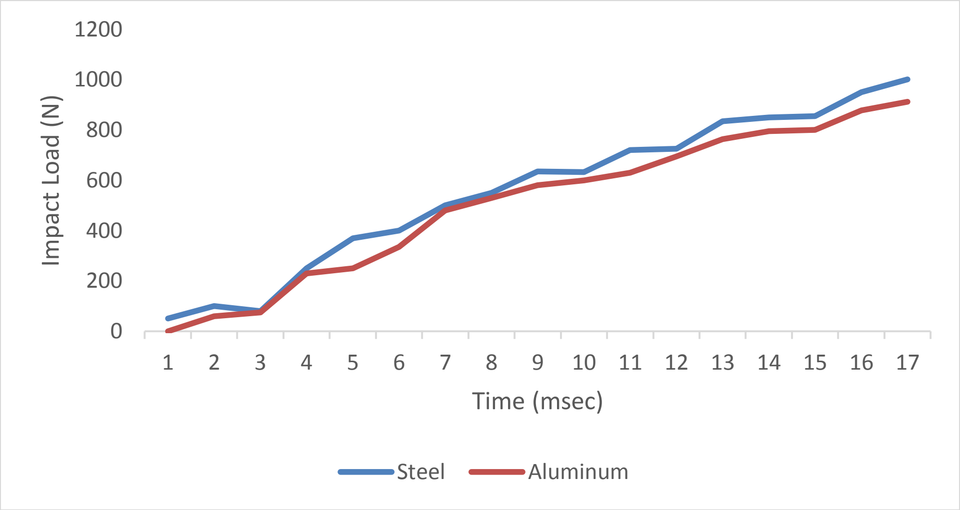

Figure 7. 1 Steel and aluminum impact comparison

The next parametric study was conducted for the change in velocity of the impactor. The impactor given in the experimental setup is used the way it is. The velocity is given as 5 m/s and 6 m/s. The maximum damage is high as compared to that of the velocity used in the experiment. Since the velocity is more, the impact damage would be greater too. Following is the table comparing the impact force vs time for velocities 5 m/s and 6 m/s.

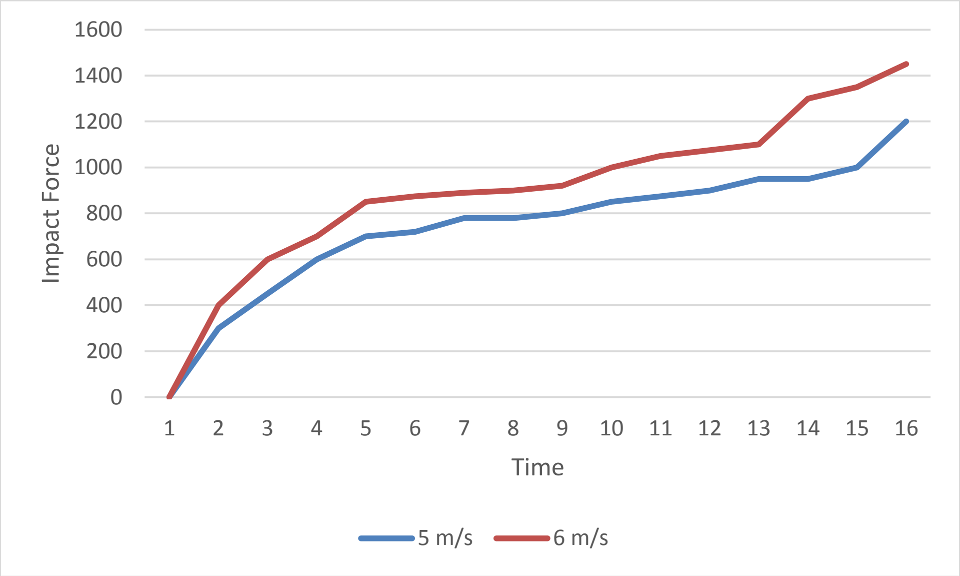

Figure 7. 2 Comparison of impact force of different velocities

8. Conclusion and Future Work

8.1. Conclusion

In order to simulate low velocity impact scenario on a composite material Finite element method can be effectively used. A Finite Element Analysis model of E-glass/epoxy and impactor were successfully modeled and developed to analyze their behavior during low-velocity impact analysis. The results from the FEM simulations matches and are in good accordance with the experimental data.

The ideal patch shape analysis was done. Keeping the surface area of all the patches as constant. All the different patch shape geometries were compared to each other on the basis of stress concentration. Elliptical patch shape had stress value of 13.54 MPa and displacement 0.447 mm. It was evident from the results that elliptical patch shape is the ideal patch for the model. The stress concentration on the elliptical patch shape was the least as compared to the other patch shape geometries. Also, it is proved that square patch is not the ideal one.

After the analysis of the patch, the model was subjected to parametric studies. In order to understand the difference obtained by change in the material nature of the impactor on the impact damage, two different type materials were used. Aluminum and steel were used as the impact material on the composite for the parametric study. It was found that the impact energy due to aluminum as well as steel impactor increases with time at a similar constant ratio. The impact force was highest for the steel impactor giving 1000.5 N while that for the aluminum impactor was 912 N. The change in velocity of the impactor was also checked in the parametric study. The experimental tests had velocity of the impactor as 4.472 m/s. The increase in velocity of the impactor for the parametric study gave high values for the maximum impact force. The damage caused by both these velocities gave excessive distortion for the laminate.

8.2. Future Work

Composite materials are orthotropic i.e. material properties are depended on directions. So, it is recommended that in order to achieve more accurate results of the finite element analysis with the experimental results, it is necessary to have defined all the constitutive properties and the failure parameter.

The ideal patch shape analysis that is simulated by FEM can be conducted experimentally. This can be further made to optimize for even better shape of the patch using optimization software. CFRP is also a composite material that is used on a large scale for composite patch repair. Same experimental and FEA tests can be conducted using this material. Later the results of CFRP and E-glass/epoxy can be compared to each other in order to get the optimized composite patch shape for low velocity impact testing.

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