Damage in composite-metal adhesive joints under low velocity impact conditions

Author

Muhammad Umar Bin Ashraf

Regn Number

00000362353

Supervisor

Dr. Aamir Mubashar

DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

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Author

Muhammad Umar Bin Ashraf

Regn Number

00000362353

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Thesis Supervisor:

Dr. Aamir Mubashar

Thesis Supervisor's Signature: ______________________

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We hereby recommend that the dissertation prepared under our supervision by: (Student Name & Regn No.) **M. Umar bin Ashraf (362353)**

Titled: **Damage in composite-metal adhesive joints under low velocity impact conditions** be accepted in partial fulfillment of the requirements for the award of **MS** degree.

Examination Committee Members

1. Name: Dr Izhar Ullah Signature:

2. Name: Dr Emad Uddin Signature:

3. Name: Dr Adnan Munir Signature:

Supervisor's name: Dr Aamir Mubashar Signature:

Date: 02 Aug 2023

Head of Department

4-8-2023
Date

COUNTERSINGED

Dean/Principal

Date: 4-8-23

Thesis Acceptance Certificate

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Signature: ____________________

Name of Supervisor: Dr Aamir Mubashar

Date: 02 Aug 2023

Signature (HOD): ____________________

Date: 4-8-2023

Signature (Principal): ____________________

Date: 4-8-23

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Dr. Amir Mubashar

Signature:

Dr. Aamir Mubashar
Professor
Department of
Mechanical Engineering
SMME NUST, Islamabad

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Abstract

Since the advancement of science and technology, the field of composites has moved from basic composite material such as wood to strongest composite materials such as graphene. Unfortunately, the cost of the most advanced composite materials is very high mainly due to their production processes. Considering the cost factor, we need to work on reducing the cost of composite materials without altering their other properties mainly their strength. Composite materials are known for their excellent stiffness to weight ratio and strength to weight ratio. The most known composite materials are fiberglass, Kevlar, carbon fiber and basalt fiber. Carbon fiber is the most widely used composite material since it has a high strength.

The drop test impact is a very short duration phenomenon with impact time being less than 20milliseconds. The material for the target point and its geometry plays a very important role in the phenomenon followed by certain boundary conditions. The impactor possesses gravitational potential energy and on striking that energy is absorbed by the targeted patch. The impactor with Gravitational Potential Energy less than the energy absorbing capability of the composite material only damages the composite patch in terms of cracks, some indentation or delamination of the composite patch layers. But if the Gravitational Potential Energy is greater than the energy absorbing capability of the composite material, the impactor will penetrate through the composite material leaving a hole. Hence the amount or intensity of the damage in composite patch is directly related to the energy absorbing ability of the composite patch.

In current study, the behavior of three different combinations composed of basalt fiber and flax fiber were studied. The 3 combinations include BF_4B_{11}, BFB_5FB_5FB, $B_5F_3B_5$ (Asymmetric, symmetric and sandwich) respectively. The test specimen was composed of Aluminum 2024 of thickness 3mm bonded with one of the circular shaped composite patch of thickness 3mm. Single impact strikes were carried out on the targeted composite patch at certain energies with aluminium plate acting as back plate. The numerical results along with graphs were taken from the software followed by the results gathered through studying damage caused due to indentation and by investigating the propagation of cracks formed. All of these results of the 3 combinations were thoroughly checked and a comparison between the 3 combinations was carried out involving the amount of indentation, force displacement, bending stiffness, damage area and cracks propagation. It was found that among the 3 configuration layups Asymmetric performed better than symmetric and sandwich layups.

Key Words Used: composite materials, basalt fiber, flax fiber, Asymmetric, symmetric and sandwich, drop test impact.

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1. CHAPTER 01: INTRODUCTION

Composite materials can strongly be used as a better alternative of structural material during the construction of different parts such as vehicle bodies. The so-called phase “replacement phase” has already been successfully passed by the structural design of composite parts. The industries (Automotive, wind power, marine, aerospace) and composite materials go a long way. In the earlier times, airplanes and ships were made of wood (spruce) and fabric but because of the industrial revolution along with the boom in the era of science and technology and due to the need of increasing the performance of such machines weather by decreasing the weight of the materials being used or the need to attain high speeds, invention and usage of new composite materials with high strength and lesser weight were now the necessities of these industries. So, the materials being used these days in the manufacturing of different vehicles, ships and aircrafts are mostly aluminium composite, carbon and glass fiber-reinforced plastic (CFRP and GFRP respectively). There is a “demonstrative phase” still going on for some of the composite materials to see that whether that composite material could be used as an energy absorber or not when replaced with any part.

LVI (low velocity impact) is defined as impact velocity less than 10m/s, and the sensitivity of composite materials to low-velocity impact is a serious problem for many industrial applications such as aircraft, maritime, and wind power. Low velocity impact causes BVID (barely visible impact damage) and it is most dangerous of all the other damages that is because it is very common one. Along with this the repairing of BVID is a bit difficult because of the fact that the damage can’t be seen through naked eye. Low velocity impact causes indentation which results in internal damage which can be in the form of fiber failure, delamination of the composite material, matrix cracking or even leaving, from a little indentation to no indentation on the impact surface. These types of damages need to be observed through some advanced and specialized techniques in order to carry out proper assessment for example X-ray tomography or ultrasonic C-scans.

Because of its great strength and stiffness, carbon fiber is frequently employed in various composite materials. They also have high thermal and electrical conductivity. Along with this they are corrosion resistance. Carbon fibers are produced from organic polymer which undergoes the carbonization process. Most of the carbon fibers made from polyacrylonitrile (PAN) process are used in automotive and as well as aerospace industry. Pitch is also another type of carbon fiber, but it is used in smaller quantities that is almost 10% of the carbon fibers are made from pitch process. The only thing which hinders or resists the use of carbon fibers are its production cost and its negative impact on environment. The cost of carbon fibers is high and its production causes greenhouse gases. So, in order to produce cost efficient as well as ecofriendly composite material with almost all the similar properties that of carbon fibers, we will be using basalt fibers instead of carbon fibers.

Basalt fibers are made from basalt rocks once they have undergone a whole proper process after being melted. Basalt fibers are cheap as compared to carbon fibers. Not only this but basalt fibers are environmentally friendly. Basalt fibers show good strength, have high working temperature range or they are resistant to fire. In terms of strength basalt and carbon have almost similar strengths. Under compression basalt fibers have high strength than carbon fibers.

The other material being used is flax which is natural fiber. A lot of research has been carried out on other natural fibers for example hemp and jute etc. So, in this work we will be taking flax into consideration. Flax being biodegradable makes itself useful for experimentation purposes. Unlike hemp and jute, flax has lower density which makes it soft hence it’s less abrasive to processing equipment Because of its lower density, flax is utilized in the automobile industry since it decreases transportation costs for other products made of natural fiber composites, as well as fuel consumption and pollutants. Considering the strength, flax has a higher value than hemp and jute. Flax fiber has a larger diversity of mechanical characteristics, necessitating research into the flax fiber strength distribution when combined with other materials.

In this research, the composite patch made will be bonded with the aluminium alloy 2024-T3 plate which will be acting as a back plate as shown in fig 1. The impact on composite patch will be taken under study through experimentation using drop test tower. The experimentation provided the real-time data for the problem. Hence the main concern of this work being carried out is to come up with, analyze and discuss the results obtained during low velocity impact testing experimentation conducted on basalt/flax composite material. This is followed by analyzing this composite material impact behavior through energy viewpoint also. The setup used for the experimentation purpose was very simple and easy and same setup could be used for testing other composite plates with ease too.

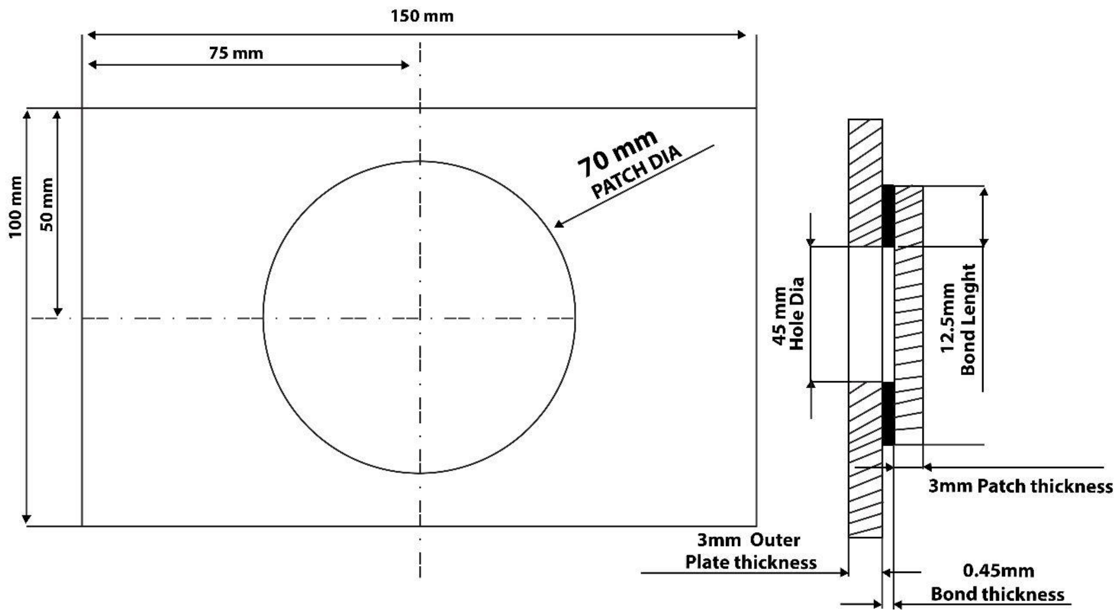


Figure 1. Dimensions of the specimen

1.1. Motivation and Scope of research

With the advancement in the industries like aircraft, marine and defense, there is an increasing need of producing better composite materials that can be used as structural materials having higher impact resistance in order to provide protection against LVI and HVI.

1.2. Objective

The main objective of this study is to investigate the damage and impact resistance of 3 types of composites under LVI, made up of same materials but with different combinations. The objectives were achieved by carrying out experimental tests and then analyzing the damages and cracks formed due to impact.

2. CHAPTER 02: EXPERIMENTATION

The impact resistance of a fiber reinforced composite was examined using a drop test tower with respect to the ASTM D7136 test methodology. Figure 2 depicts the test setup used. The impactor's geometry or form was cylindrical, with a diameter of 16mm. The impactor tip at the end had a hemispherical form. The combined weight of the impactor body and carriage was 7.67kg. An aluminium plate (2024-t3) of thickness 3mm and a composite material of basalt/flax was used. Both of the adherends had gone through the process of surface cleaning. Aluminium plate of dimensions 150mm by 100mm with a hole of 45mm in the center was used. A circular patch of composite material having diameter of 70mm was bonded onto the hole of aluminium plate with a bonding solution. The bonding solution used was a combination of an adhesive (araldite Ly 556) and a hardener (aradur 22962). The specimen was cured in a heating oven for 2 hours at 100^{o}C for making a perfect and strong bond between two adherends. Once the specimen was cured it was placed and clamped in the drop test tower. The clamps used had rubber dampers at the end which absorbed the vibrations that were caused due to the impact. Impact tests were then carried out on all the specimens used, at different energies. In all the experimental tests, the releasing height of the impactor was changed in order to perform impact at 3 different energies as shown in table 1. The releasing height that was to be kept was calculated by applying equation of energy conservation which is E=mgh, where, m= total mass of the impactor,

g= gravitational acceleration,

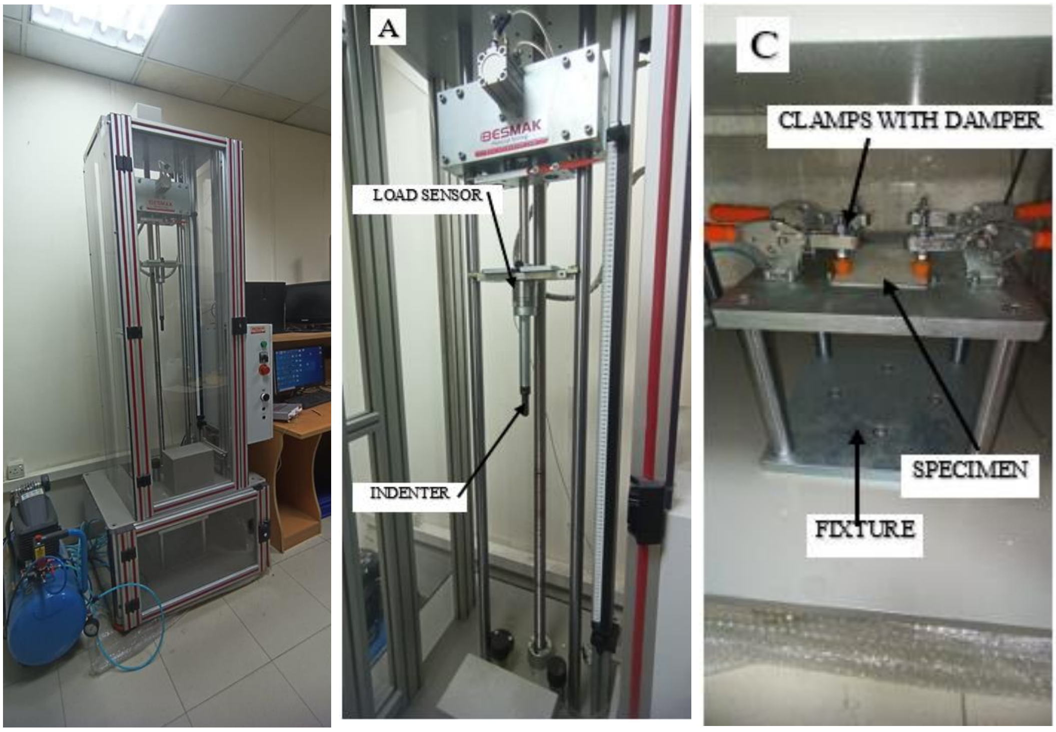
h= release height of the impactor and

E= potential energy of the impactor.

Table 1. Low-velocity impact tests, at 15J,25J AND 50J energies.

Impact scenario	Specimen type	Impact energy (J)	Velocity (m/s)	Drop height (m)	Drop mass (kg)	No of Samples
Single impact	3D-Asymmetric, Symmetric & Sandwich-FRC	15J 25J 50J	1.98 2.55 3.61	0.20 0.33 0.66	7.67 7.67 7.67	4 4 4

Single impact tests were carried out on all three composite materials. In case of single impact, each composite material was striked once using different energies i.e. 15J ($V_{impactor}$=1.98m/s), 25J ($V_{impactor}$=2.55m/s), 50J ($V_{impactor}$=3.61 m/s) in order to study the behavior of all 3 composite materials under LVI i.e. rebound, penetration and perforation. This was done to see the maximum amount of energy each composite material can absorb before having a hole in it. The data collecting system captured various information such as impact force, impact velocity, and impact energy.



(a) (b) (c)

Figure 2. Experimental setup used for testing.

2.1. Material Used

The primary reinforcement materials used in the current research of Bio-Hybrid composite materials were carbon fiber and flax fiber. Basalt Fiber Fabric cloth 200 GSM twill weave 13 having thickness of 0.3mm was obtained from China through local vendor, Zalan Technologies situated in Islamabad, Pakistan. Flax 2x2 twill fiber cloth 300 GSM was procured from Easy Composites United Kingdom. Thermoset resin system, Epoxy YD-127 was used to fabric the composite panels. Epoxy resin is the most common type of matrix from the category of thermosetting polymers. It is basically a synthetically made matrix and is used as adhesives in many applications such as aerospace, automotive etc. Epoxy resin is used in making polymer matrix composites in various mixing ratios. Epoxy is mixed with hardener. The different ration of mixing results in different mechanical properties. Therefore, the mixing ratio needs to be clearly defined and investigated before being used in the manufacturing. The quantities should be very accurate. Both the hardener and the epoxy need to be accurately measured using weight scale.

2.2. Fabrication Process

In this research, three types of Basalt/flax composite laminates were manufactured using vacuum bagging method. The stacking sequences used in the study were sandwich [B_3F_3B], symmetric [BFB_2FB_2FB] and asymmetric [B_5F_3B]. To manufacture the composite laminate, primary reinforcements basalt and flax were cut in square layers according to the ASTM D7136 standard specimen size. Prior to the vacuum bagging process, epoxy and hardener were mixed with a ratio of 2:1 and were stirred. The steps involved in the vacuum bagging process is given in the figure. A glass panel was used a mould. Curing time of 6 hours was used in this process to ensure the perfect curing and to avoid the voids. After the fabrication of composite laminates, Hacksaw was used to cut composite laminate plate to make specimen according to the ASTM standards.

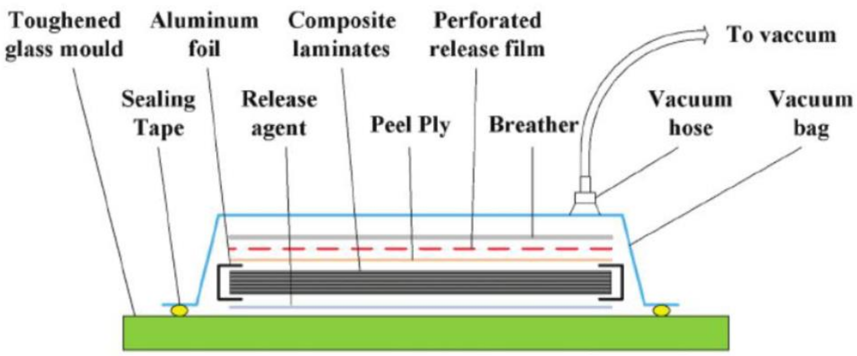


Figure 3. Step by step process involved in the vacuum bagging process.

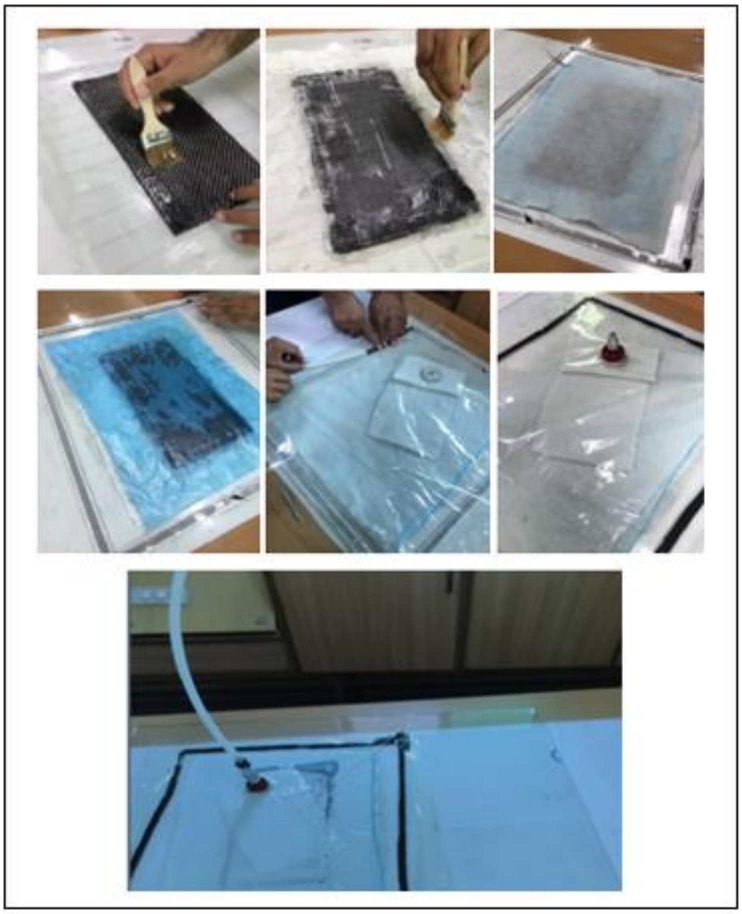


Figure 4. Step by step process involved in fabrication process of basalt/flax composite material

3. CHAPTER 03: LITERATURE REVIEW

3.1.1. Introduction

In the preceding section, a complete understanding of impact loading and its effects on different composites materials will be developed. Low velocity impact works carried out primarily will be reviewed. The impact loading mainly through drop weight impact will be discussed. The literature review is ultimately summarized at the end of this section.

3.1.2. What are composites

Composite materials are made up of two different types of materials with distinct physical and chemical characteristics. This combination leads in the development of a novel material with a unique mix of qualities.

3.1.3. Types of composites

There are three types of composites;

1) Particle-reinforced
2) Fiber-reinforced
3) Structural

3.1.4. Classes of composites

1) Polymer Matrix Composites
2) Metal Matrix Composites
3) Ceramic Matrix Composites

3.1.5. Reusable composite

Reusable composites are made from combination of different materials which include glass fibers, carbon fibers, basalt fibers, resins and plastics. All of these materials are combined in a number of ways for example hand layup and vacuum assisted bagging process. This results in the formation of more strong, durable and lightweight composites. The molding of the composite material into desired shape is followed by its curing at high temperature and pressure. One main example of reusable composite material is thermoplastic composites because they could be reshaped multiple times after being heated keeping it structural integrity intact. Moreover, reusable composites apart from saving money on materials helps in reducing environmental impact.

3.1.6. How composites are manufactured

Reinforcing fibers in a matrix resin results in the formation of composite materials. Hand layup and vacuum assisted bagging process are mainly used. reinforcing fiber plays the role in providing stiffness and strength of the composites while the matrix provides the environmental resistance and rigidity of the composite.

3.1.7. Different composite materials and their applications

Table 2. Fiber composites and their use in aircraft [1]

Materials	Applications
Carbon/epoxy	It is used in key structural and skin materials.
Kevlar/epoxy	In military applications, it is often used in primary structural and armour plate.
Glass Fiber	Used in structural and skin material
Glass/phenolic	Used in interior design, furnishing, and construction.
Boron/epoxy	Composite repair patches and older composite objects use it.

3.1.8. Significance of composites

The most important challenges faced by the defense, vehicular and aerospace industries these days is to decrease the fuel usage that is increasing fuel economy and decreasing the cost along with weight and damage without compromising or sacrificing the performance. This purpose is served by using composite materials which are low weight and provide high strength hence more resistant to damage.

3.2. Types of impacts

There are two types of impacts;

1) Low velocity impact
2) High velocity impact

3.2.1. Low velocity impact

Impacts which occur in the velocity range of 1-10 m/s depending on the properties of material, projectile mass and stiffness are known low velocity impacts[2]. Low velocity impact is regarded as the most harmful load on composite laminates, and typically occurs during maintenance and in-service operations. Low velocity impacts are considered dangerous because of the barely visible damage they produce. Izod and Charpy Impact Tests, as well as the drop weight test, are used to perform low velocity impacts. the advantage of using drop weight impact testing unit is that it allows the simulation of wide variety of real world impact conditions helps in collecting detailed data of performance[3]. A wide variety of test geometries and complex components can be examined and tested using Charpy and Izod tests[4]. Researchers have used Charpy impact tests in more advanced ways in order to measure force more efficiently and accurately by using high speed photography and to obtain results which shoe crack propagation[5].

Table 3. Types of Low Velocity Impact Tester [6]

Methodology	Main Function
Izod and Charpy Impact Test	
By placing a notched specimen into a large machine with a pendulum of a weight. The pendulum is raised up to a certain height and allowed to fall. As the pendulum strikes, it impacts and breaks the specimen, rising to a measured height.	i. To test the impact toughness of the material ii. To compare composites with different layups, including woven and unidirectional laminates.
Drop Weight Test	
A mass is raised to a certain height and released, impacting the specimen.	To test the impact behaviour of composite plates.

3.2.2. High velocity impact

At the time of take-off and landing the structural parts and equipment of airplane which are prone to high velocity impact loading include turbine blades, intake of engine nacelle, radome and radar antenna. One major example which is the cause of high velocity impact is bird strike, this is because of their high probability of occurrence[7]. Bird strike results in the instant damage and material failure. Immediate material failure takes place due to severe damage caused due to high velocity impact [3]. Composite used in the structure of A330 commercial aircraft is shown in fig 3.

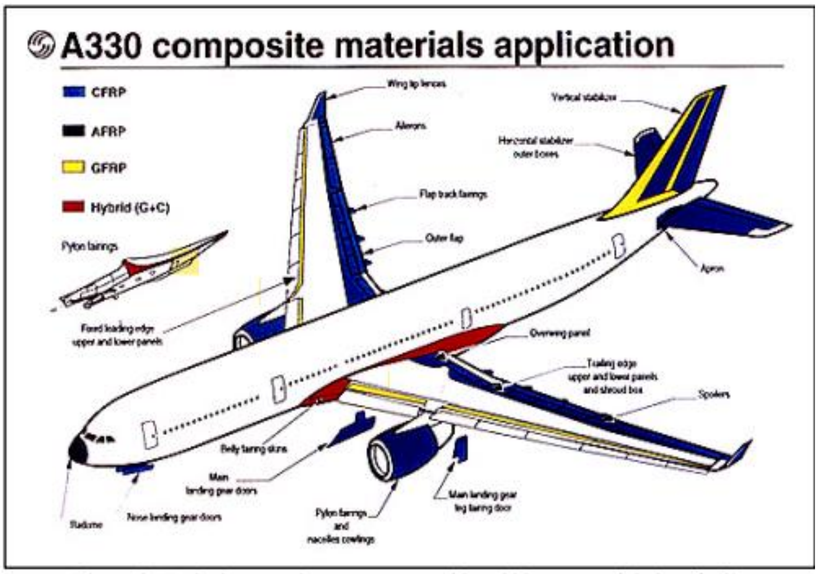


Figure 5. Composite used in structure of A330 commercial aircraft [8]

3.3. Performance of different adhesives under impact loading

Adhesive are used to form a joint between composite material and the metal. As a replacement of heavier conventional joints e.g. weldments and bolts, adhesives are used. adhesives are used in both low velocity impacts and as well as high velocity impacts. Impacts are categorized into two parts; low velocity impacts and high velocity impacts. A moving or static body may experience any of these impacts or both of them. In both impacts the body experiences a degradation in its strength. The degradation in material strength depends on the impact energy. More the energy more the materials strength degrades. Once the impact energy surpasses the energy absorption capability of material, a clean hole is produced in the material. Among the two type of impacts, low velocity impact is more dangerous because this impact causes barely visible damage in the material. Many studies have been carried out on effect of low velocity impacts on both materials and adhesives.

Galliot et al. [9] using modified drop weight impact test found how the adhesively bonded lap joints behave dynamically in shear failure (mode II) between impact velocities of 1m/s and 4m/s. Galliot et al results showed that as the loading rate increases the stiffness, the absorbed energy and the failure load also increases. Goglio et al. [10] using split Hopkinson pressure bar explored that a bi-component epoxy adhesive is very sensitive to strain-rate.

Kenneth Gollins et al [11] experimentally examined the mechanical behavior of two adhesives (a methacrylate and an epoxy) under low velocity impact. This was done to see whether the adhesive joints possess enough survivability under impact loading. A circular steel patch was bonded with a steel plate using both methacrylate and an epoxy one by one. The average static bending strength of the methacrylate and epoxy adhesive joints was 13.5MPa and 13MPa, respectively. According to Jonas-Lambert model the critical failure velocity of methacrylate was around 170m/s and that of epoxy was around 320m/s. The energy absorption of adhesive at critical failure velocity of steel-Methacrylate is 4J and that of steel-epoxy is 16JTo measure the decrease of adhesive bond strength as the dynamic load approached the failure load, residual strength tests were performed. These experiments revealed that when the dynamic load rose, structural deterioration occurred inside the adhesive bond. According to the micrographic results of the failed adhesive surfaces, under dynamic stress, the epoxy glue operated like a ductile material rather than a brittle material, but the methacrylate acted the other way, that is, like a brittle material. The critical failure velocity for both methacrylate and epoxy, the average critical failure force and energy, the energy absorbed by the adhesive under impact loading, and the kind or nature of the bond failure, whether cohesive or interfacial, were all evaluated through testing.

A. Maurel-Pantel et al. [12] tested and compared 3 different adhesives using drop weight impact test rig incorporated with modifies arcan fixture. For the last 20 years, complex structures are being widely and increasingly integrated with structural adhesive in order to reduce mass specifically in the area of engineering particularly civil and in the field of transportation. So, we need to find out the adhesive having optimal adhesive forces which would then allow to make a decision about the multi-factorial trade-off. One thing which must be considered is not to sacrifice structural performances nor creating new areas of vulnerability while reducing the weight. To find out which adhesive is a best fit, experimental test are to be carried out to characterize the mechanical performance of the adhesives. According to several publications, the behavior of adhesive joints under impact is complicated and is impacted by joint shape, adhesive characteristics, and loading modes. Modified arcan fixture was used for performing static tests. For characterization of impact strength, the specimen should be imposed by the dynamic loading. Two types of dynamic loading include, “high speed loading” and the second is “shock elastic wave type”.

Arcan fixture consists in loading an assembly that is adhesively-bonded along a controlled axis which ultimately forms and angle between 0^o and 90^o with the axis sample. Modified arcan fixture is used for performing static tests[13]. Combined tension-shear load mode takes place of the bonded joint when a load in various directions/orientations is applied. It is made up of several attachment points with two half discs along with the perimeter. For setting up this device on a tensile testing machine these attachment points are very helpful. Considering these tests or investigations cylindrical specimens are used in arcan system. Flanges with rubber dampers are used for holding and positioning of the test specimen. The uniformly distributed screws on the periphery are used to fix the sample using flanges. So, during testing phase for both traction and shearing as the mass of impactor along with release height increases the load also increases.

Before conducting experiments, an optical microscope is used to perform optic control, specifically to examine the alignment of two surfaces, particularly for cyanoacrylate glue. The lease dispersion across all experimental results is of 3M™ 2216. The araldite adhesive has a low dispersion in mode II but has a higher dispersion in mode I that is greater than 10%. The adhesive having high dispersion in both mode I and mode II is cyanoacrylate. Even cyanoacrylate has a coefficient of variation more than 10%. This result is predicted since the glue has a low thickness of roughly 0.01mm and brittle behaviour, making it susceptible to bonding flaws. The modified arcan set-up introduction made it possible to perform tests in shear and tensile configurations on each specimen with different free edge geometries.

Using stress point criterion, the results of static tests were used to find the critical shear and tensile stresses $\sigma_{c,II}$ & $\sigma_{c,I.}$ the second phase of this work was the experimentation where impacts were to be carried out on the adhesive in joints in both shear and traction for all 4 different geometries that are (straight edge, sharp edge, beak edge and rounded edge). Characteristic energies (E_0 and E_{100}) of each adhesive were defined using these impact tests. For each edge geometry and for each adhesive the relative impact strength ISO values are determined.

The static tests showed that for the ductile adhesive (3M™ 2216) the influence of the edge geometry is very less contrary of that of the other two adhesives which are Cyanoacrylate & Araldite. The adhesive which is very much low in static performance is 3M™ 2216 and for a relatively low benefit in dynamic performance. Hence after conducting all he experimentation, it was seen that both the dynamic and static behaviors of adhesives were different. So, the nearest or the best compromise between dynamic and static behavior is not easy to find.

3.3.1. Performance of composites under impact loading

Different composites behave differently when subjected to impact. This is because of their different combinations and different physical and chemical properties.

3.3.2. Performance of CFRP under ballistic impact

Sidney Chocron et al [14] conducted research using ballistic testing, material tests, and computer simulations to assess the impact on various materials, particularly composite materials, which are commonly utilized these days. Because of high value of specific strength and stiffness value carbon fiber are very common in aerospace industry, recreational sports and automotive industry. Carbon fiber apart from being proving to be light weight in structures and being stiff and strong, they have very poor impact performance as compared to other materials being used these days. Under high velocity impact 2D composite perforate while under low velocity impact these same 2D composites can delaminate. Unlike polymeric fibers such as Kevlar carbon fibers are brittle and their energy absorption capability is low which is why Kevlar is more efficient under ballistic impact. The qualities of the material (carbon fiber) were found using simulations that replicated the material tests. 2D CFRP materials with two different thicknesses of 6.35mm and 25.4mm were used and subjected to ballistic impact tests. Along with 2D CFRP, 3D CFRP material of two thicknesses i.e. 6.35mm and 25.4mm were also used.

Torsional, Hopkinson bar tensile and compression tests, ballistic, and through-thickness tensile tests were performed. Because the Hopkinson bar equipment is incapable of evaluating big testing specimens, small testing specimens were tested in tension [15]. Ballistic tests of two types were carried out with carbon fiber single yarn ballistic impact being the first one and ballistic impacts of composite being the second one. The primary goal of ballistic impact on single yarn is to determine whether or not wave propagation in carbon fiber follows classical theory. While the computer material model created for this programme was validated, ballistic impact on composites was performed. The parameters that were determined through ballistic impact were residual velocity, impact velocity, and the ballistic limit of every composite under consideration. Along with this the displacement history of the target from the back side.

Torsional tests show that as the rotational angle increases torque increases. Tensile tests showed that with increase in % strain the stress value increases until the failure of material occurs. The projectile was not exactly in line or aligned with the yarn during the single yarn ballistic test, and some fibers were left behind after they slipped away. The experiments' findings clearly revealed that, in the case of carbon fiber, the best element to use for mesoscale computations would be entirely integrated components that reflect the fiber's bending stiffness. The primary findings of this experiment were that the decrease in strength for tiny specimens as compared to big specimens is most likely due to gripping artefact. Moreover, other than the gripping artifact the tensile properties of 2D and 3D composites are similar. Under shear 3D tests specimens proved to be stronger than 2D specimens. Ballistic tests determined that the ballistic limit of both 2D and 3D composite having same areal densities is not different. Through computer simulations the mechanical tests carried out which include torsion, tension and through-thickness tension tests were captured properly. Even for the 2D and 3D panels the computer model captures the deflection vs time quite well. The model obtains the ballistic limit by using material parameters which were obtained from mechanical tests without including any effects of strain rate.

3.3.3. Performance of E-glass and natural fiber helmet under LVI impact

Plastics are being widely used in many products these days e.g. in helmet manufacturing. More use of plastic proves to be hazardous not only to human health but also for the environment because of the pollution it creates when burned. Along with pollution it creates problems such as plastic is non-biodegradable and its cost. So, keeping in view these things damage resistance of natural fiber helmet and E-glass helmet was evaluated by Ravi Y.V. et al [16] using drop weight impact test. Natural fiber helmet is made up of hybrid hemp-banana. Due to less awareness of natural fibers and their performance they have had not been used to that much. Hence through research the best use of hemp-banana helmet came up which will ultimately reduce the dependency of helmets made up of other materials i.e. E-glass. Drop weight test was carried out on both the helmets i.e. helmet made up of natural fibers and the other made up of E-glass. For replacing plastic and synthetic fibers natural fibers are the best option. Moreover, natural fibers are free and are present in abundance.

Under normal loading conditions the damage is not that much dangerous as compared to damage caused due to impact loading[17]. The main and most important parameter for helmet manufacturing industries is the study of failure caused due to impact loading. In a helmet body the surface of the helmet absorbing the maximum amount of impact load is the top surface of the helmet body and not the other sides of the helmet[18]. Thickness, angle of stress pressing on the composite specimens, malleability, and weight are some of the material qualities that influence impact force [19].

Drop weight impact test was carried out on 2 helmets, one made of E-glass (synthetic fiber) and the other using hemp-banana fiber (natural fiber). Both the helmets were kept on the rigid base one by one and mass of 43kgs from a height of 2m with a velocity of 4.43m/s was applied. The results from the software were extracted and recorded. The fractured helmet was then taken for further study that is to see and analyze the crack propagation and delamination, if any. When results of both the E-glass and Hemp-banana were compared, it was drawn that the amount of force E-glass and hemp-banana helmets can withstand is 0.054 tons and 0.068 tons respectively. The amount of energy E-glass and hemp-banana helmets can withstand is 410J and 550J respectively.

Hence the material, helmet shell is made up of has a very important role in deciding the impact load effect on helmet[20]. Moreover, from the force and energy absorption ability of both the helmets it could be concluded that helmet made up of natural fibers hemp-banana have a good capability of bearing high velocity and high load as compared to E-glass helmet. Hence the helmet manufacturing companies should shift to natural fibers for making helmets instead of using other materials which would ultimately also help in saving the environment.

3.3.4. Performance of 3D thermoplastic and thermoset FRC

S.Z.H. Shah et al. [21] performed evaluation of damage caused to 3-D thermoplastic composites of glass fiber and 3-D thermoset composites of glass fiber was carried out. Both of the damaged materials were analyzed and compared. Both single strikes and recurring strikes were considered to see the amount of energies each material absorbs. Tests were carried out at a number of different impact energies. For experimentation low velocity impacts were carried out using drop weight testing machine. Laminates reinforced with 2-D or unidirectional are more vulnerable to delamination this is because fabric architecture has a very major role in improving the resistance of impact. There are a lot of studies in which the architecture of the fabric is changed or altered [4, 22-27] and for improving the impact resistance of fiber reinforced composite a toughened resin system is used[28-31]. Keeping in view of this 3-D fiber reinforced composites were made and were more widely being used in impact resistance. 3-D fiber reinforced composites are commonly used in the aircraft sector as structural materials for the principal fuselage structure, engine mounts, and wing edges. Many authors have carried out studies related to impact performance of 3D FRC under low velocity impact[29, 30, 32-36] and they concluded that 3D fiber reinforced composites as compared to 2D fiber reinforced composites have greater energy absorption capability and greater impact resistance. Along with the fabric architecture, adhesive toughness also plays an important role in increasing the fiber reinforced composite impact resistance. More the impact resistance would result in less crack propagation, reduced delamination and damage extension.

3-D orthogonal E-glass woven cloth was used in this study. The VARTM process was used for manufacturing of both thermosets based 3-D FRC and thermoplastic based 3-D FRC. Proper methods were followed in order to get the ultimate desired thermoset and thermoplastic panels. The thickness of both panels to be tested was 4mm. Single strikes at 9 different energies were carried out on both kinds' thermoset and thermoplastic specimens. Different energies were used as an input by changing the releasing height of the impactor while keeping the mass of impactor constant. Once single strikes were carried out, recurring strikes at two different energies i.e. 30J and 50J were carried to see the amount of energy absorbed by both the panels before perforation occurs in the panel.

As soon as all the tests were carried out, both the after-test panels were compared in terms of their damage. The indentation produced in the panels was measured using dial gage. The depth of indentation produced is determined by the impactor's mass and velocity [37]. The corresponding results which include force-time relationship graph, force-displacement relationship graphs which show the damage process in fiber reinforced composites[38, 39], the velocity, maximum force and amount of energy absorbed were recorded from the software. Microscopic damage characterization of the panels was carried out to find the damage propagation. The damaged area was pointed out using backlight method.

Damages were categorized in two types; micro-damage and macro-damage. Micro-damage included damage mechanisms like fiber breakage, plasticization, and matrix cracking whereas macro-damage included yarn debonding, Z-crown failure, yarn straining and surface VID. Once results were obtained and comparison of both thermoset FRC and thermoplastic FRC were carried out it was concluded that under both single strikes and recurring strikes thermoplastic FRC had reduced damage as compared to damage obtained by the thermoset FRC. From the experimental results it was seen that the thermoplastic based 3-D FRC had lesser damage area around 44% lesser than the thermoset based 3-D FRC. For recurring strikes 30J and 50J energies were used. at 50J all 5 strikes were successfully sustained by the thermoplastic based 3-D FRC without any perforation. On the other hand, the thermoset based 3-D FRC was completely perforated after the 4^{th} strike. All of these results ultimately revealed that higher impact resistance was shown by the thermoplastic based 3-D FRC along with lower loss in integrity of structure when subjected to both single and recurring strikes. This clearly tells that the suitable alternate to a conventional thermoset based 3-D FRC being used in aerospace industry is the thermoplastic based 3-D FRC.

Due to increasing demand of more efficient and low-cost composites with high strength to weight ratio, very much research is being conducted to examine the impact response and infrared radiation properties of glass fiber reinforced thermoplastic and carbon fiber reinforced thermosetting composites. where Zhibin ZHAO et al. [40] have carried out study related to this area. This research is being carried out largely because the low velocity impact response and infrared radiation characteristics of composites have seldom been addressed combined. The main application area of fiber reinforced polymer composite laminates is in defense industry and aerospace industry[40-42]. For experimentation purpose drop hammer impact testing machine also called as drop weight impact testing machine. Different impact energies which included 5J, 10J, 15J, 20J, 25J, 30J, 35J were used for the experimentation of both thermoplastic and thermoset laminate. The striked surfaces were examined and seen through naked eye first before analyzing them through ultrasonic C-scan. Seeing from the back side of the specimen the results showed that the matrix cracking in thermoplastic laminate specimen occurred at 20J whereas in thermoset laminate specimen matrix cracking occurred at 35J. When front surface was examined the matrix cracking in thermoplastic took place at 20J while in thermoset matrix cracking took place at 10J.

From the comparisons drawn with the help of results obtained it could be concluded that considering impact resistance, thermoplastic laminates showed more delamination ductility as compared to thermoset laminates. The maximum contact force of thermoset laminates is substantially higher than that of thermoplastic laminates under low velocity impact. Nonetheless, due to the thermoplastic matrix's poor ductility and bending stiffness, the difference in energy absorption between the two is not significant. Moreover, the damage detection effects of pulse thermography on thermoplastic/thermoset laminates are not same that is the thermoset laminates shoe better detection ability as compared to thermoplastic laminates. In passive thermal monitoring, the emergence of minor delamination and matrix cracking might be characterized by a composite with varied matrix, impact region inside a dark zone, bimodal temperature measuring line, and weak temperature increase effect. The weak temperature rises effect, the unimodal temperature measurement line, and the weak temperature rise effect may characterize the occurrence of severe delamination, minor fiber breakages, fiber-matrix debonding, and severe matrix cracking. The weak temperature increases effect, the hot zone, and unimodal temperature measurement might be useful for characterizing the development of a significant number of fiber-matrix debonding and fiber breakages. In terms of Hertzian forces, the Hertzian forces for each composite are distinct. The Hertzian failure is the first point on the curve with a sharp load drop, indicating the rapid spread of laminate delamination damage [43-45]. Thermoplastic laminate has a lower Hertzian force than thermoset laminate. Keeping in mind that the Hertzian force is affected not only by the kind of matrix but also by the type of fiber. This study hence concludes, that the thermosets laminates are better to use instead of thermoplastic laminates.

3.3.5. Performance of Fiber-Reinforced Polymer Composites and Their Hybrids under low velocity impact

Every material has its own impact resistance which distinguishes them from other materials. With the advancement in different industries the producing of high strength and stiffness materials having low weight has not only become necessary but challenging. In order to check the lifetime of composite materials used in structural parts low velocity impact analysis should be carried out. This is because analysis of low velocity impact is important to protect different vehicles from getting damaged. On low velocity impact testing mainly 3 types of cases may occur. First one being rebounding which is when the impact energy is not enough to pass through the specimen. Second being the penetration where the impactor gives all the energy to specimen and tears some of the layers of specimen. The last one is the perforation, which occurs when the impactor completely enters the specimen. Under low velocity impact, fiber-reinforced polymer composites and their hybrids were studied. Impact testing was performed on fiber metal laminate composites, mono composites, and hybrid composites. Caminero et al. (2017) [46] evaluated the degree of damage resistance of carbon fiber reinforced polymer epoxy composites by altering their thickness to measure the influence of composite thickness and stacking sequences. For measuring failure mechanisms micrographs and C scans were used.it was seen that with increasing impact energy there was a decrease in damage resistance and less energy was absorbed by thicker laminates. Low velocity impact is also influenced by changing of the matrix materials.

Hosur et al.(2005) [47] made four distinct woven hybrid composites and investigated their responses to low velocity impact. Vacuum assisted resin moulding using carbon and glass fabric and epoxy resin was used to manufacture the hybrid composites. It was determined that hybrid composites outperformed carbon/epoxy composites substantially.

Amuthakkannan Pandian et al. [48] performed tests in order to develop new materials that could be used in structural applications such as industries like aerospace. The enrichment of low velocity impact is based on proper selection of fiber. Delamination, fiber breakage and matrix fracture are the reason for the failure of mono fiber composites. As an alternate to high strength fiber aluminium metal laminate composites are a very good option. For the case of metal laminate composites, the main reason for the failure in composite is the delamination. Considering environmental perspective many researchers have started focusing on natural-synthetic fibers hybrid materials, this is known because of the fact that there is a decrease in the usage of synthetic fibers. When numerical approach is considered, it is just another way of analyzing the low velocity impacts on composites. Fem is mainly used for numerical approach and for simulation purposes ANSYS and ABAQUS explicit software's are used. mostly once experimental works are done, researchers' carryout or crosscheck the results using the numerical approach.

3.3.6. Performance of fiber metal laminate under low velocity impact.

A lot of studies have been carried out related to fiber metal laminates comprising of composite layers having aramid fibers, carbon and glass acting as reinforcement in a thermoplastic and thermosetting matrix. Vlot et al. [49-52] showed that monolithic aluminium sheet with same areal density as that of the fiber metal laminates didn't perform better when compared with fiber metal laminates made up of glass fiber reinforced epoxy and aluminium sheets. Fiber metal laminates having better fatigue performance, corrosion properties and blunt notch strength along with being fire resistant are mostly used in aircrafts structures[53-55].

Caprino et al. [56] studied the low velocity impact of fiber metal laminates consisting of glass fiber reinforced polymer (GFRP) and aluminum 2024-T3 layer. His research revealed that the resistance to total penetration of fiber metal laminates was greater than that of composites.

Ankush P. Sharma et al. [57] investigated the effect of through thickness metal layer distribution on the low velocity impact response of fiber metal laminates. Thermosetting resin and glass fiber-based composites have good stiffness and strength but have poor performance under impact because of being brittle. Four combinations of FMLs and composites having different configurations ad thickness were prepared and tested. The distribution of the aluminium layers over the thickness reduced the maximum force; however, this is only true for a certain degree of energy absorption. When thin sheets were used on impact surface as well as on the rear face, the cracks started forming up at low impact energy levels and the cracks formed were of large size.

Previously a lot of work has been carried out and studied related to low velocity impact loading on different composite materials. The composite material which is not studied to a great extent and still needs testing in order to find its different properties is he combination of basalt and flax fibers. In this research work we will be studying as well as analyze the impact resistance of basalt/flax composite material when bonded with aluminium plate (2024) of thickness 3mm under low velocity impact loading using different composite configurations which include Symmetric, Asymmetric and sandwich.

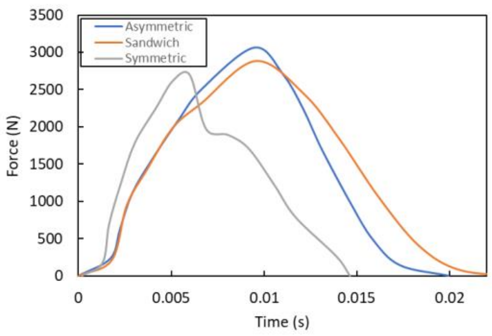
4. CHAPTER 04: RESULTS AND DISCUSSIONS

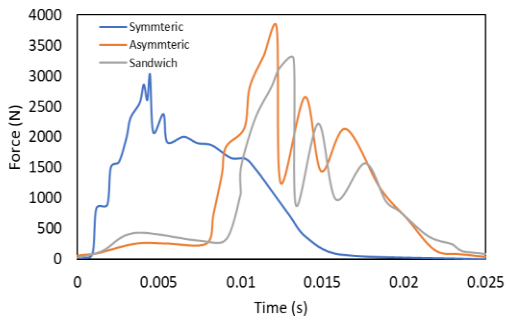
4.1. Single impact test

Once the tests are carried out, the impact performance of all 3 basalt/flax based 3D-FRCs combinations are compared and analyzed with respect to force-time and impact resistance (damaged area and permanent indentation) due to single impact. In addition to this, damage and propagation of cracks formed in all 3 combinations were studied.

4.1.1. Force- time and force-deformation graphs

An illustration of the relationship between force and time is called a force-time graph, often known as a force vs. time graph or a force-time curve. Force-time curves shows you that how the materials have acted when the force is applied with respect to time. Force-time graphs can provide information about the nature of object interactions, such as an item's acceleration or deceleration, the size of a force exerted, or the presence of external forces operating on a system. At 15J energy all of the basalt/flax configurations have experienced forces with very little difference, still asymmetric among all three has experienced the most force. Similar is the case at 25J and 50J but here the force experienced by Asymmetric is higher than Symmetric and Sandwich. This shows that the asymmetric configuration of basalt/flax composite has greater ability of withstanding force.





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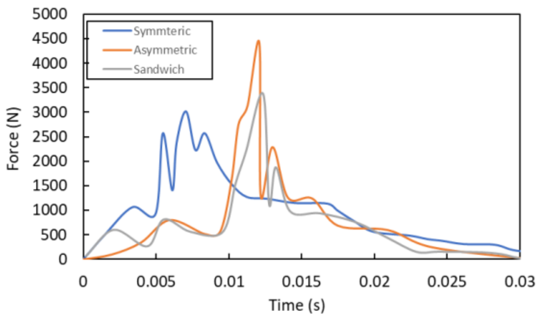

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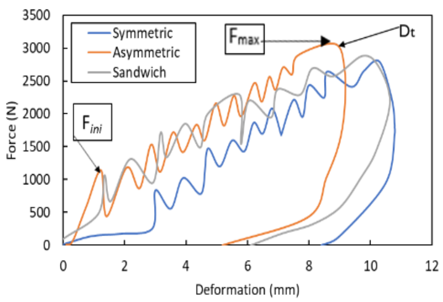
Figure 6. Comparison of force-time curves of all three combinations at different energies i.e. (a) 15J, (b) 25J and (c) 50J.

The slope of the force-displacement curves from these tests shows the bending stiffness or dynamic modulus of the material [58]. During a test, a change in its slope tells the transition and spread of damage within the specimen. At 15J, the asymmetric and sandwich configurations have shown a higher deflection whereas in terms of bending stiffness symmetric and sandwich have shown a lower bending stiffness than asymmetric.



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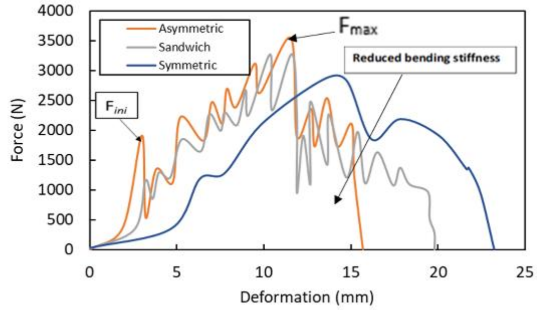

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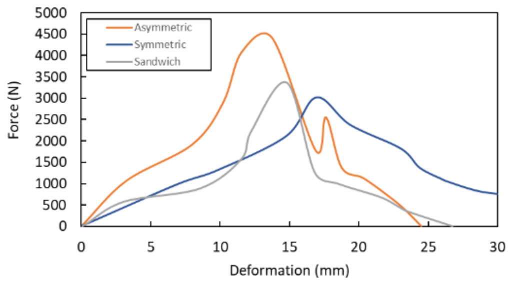

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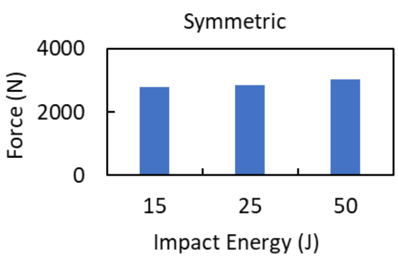
Figure 7. Comparison of force-deformation curves of all three combinations at different energies i.e. (a) 15J, (b) 25J and (c) 50J.

4.1.2 Force-energy, indentation-energy, peak force deformation-energy response and bending stiffness-energy response

Force-impact energy relationship is particularly useful in studying the behavior of objects during collisions and understanding the transfer of energy involved. The general relationship between impact energy and force during collision or impact event is that an increase I force typically leads to an increase in impact energy. The force energy graph clearly shows the behavior of increasing impact energy on force with varying combinations of baslat/Flax-FRCs as shown in fig 6. The effect of impact energies on force in case of Symmetric combination is very small, while on the other hand Asymmetric has a significant effect, Sandwich being in between both combinations. The maximum force experienced by all the three Symmetric, Sandwich, Asymmetric is 3.02kN, 3.37kN and 4.41kN respectively.



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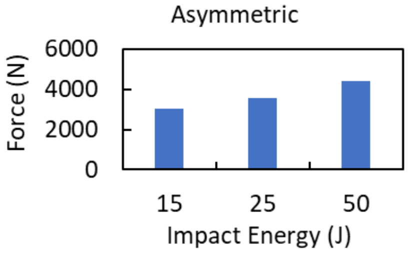

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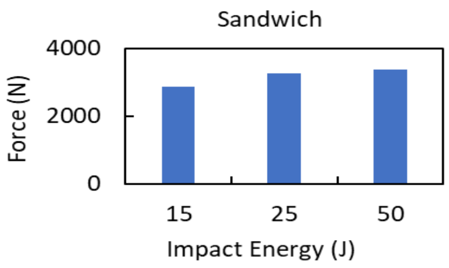

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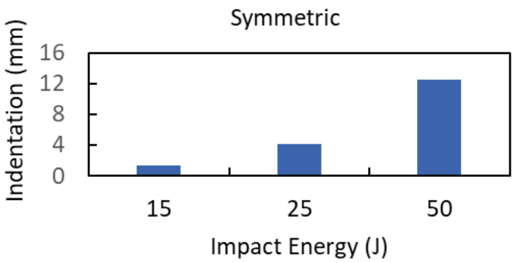
Figure 8. Comparison between Force-energy of all three combinations at each impact energy.

The moment the indenter strikes the specimen, it passes on the energy it possesses onto the specimen causing damage in the shape of dent on the surface of specimen. As the energy increases the indentation also increases in all three combinations but not in same ratio. In case of symmetric the overall indentation caused due to all energies is minimum as compared to Sandwich with overall maximum indentation over all energies as shown in fig.



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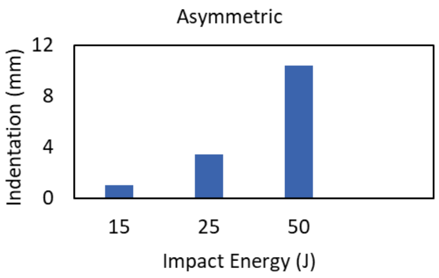

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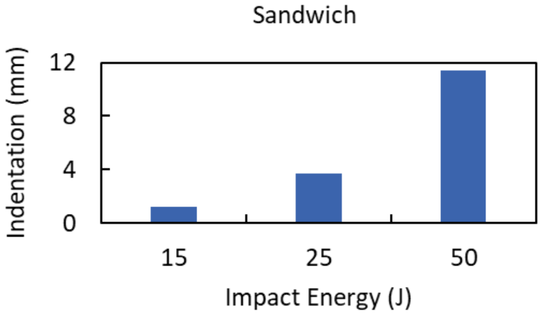

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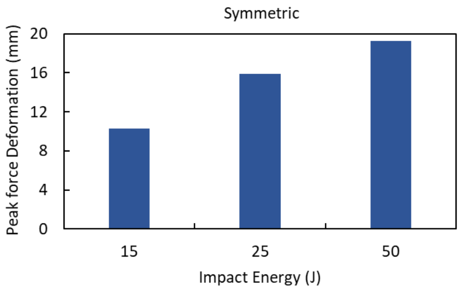
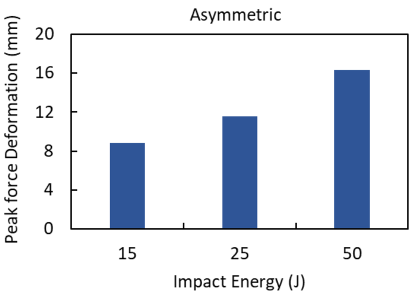
Figure 9. Comparison between Indentation-energy of all three combinations at each impact energy.

Fig.8. depicts the trend of deformation of the 3 configurations and 15J, 25J and 50J energies. Generally, the deformation in asymmetric is overall less as compared to other two at maximum force.





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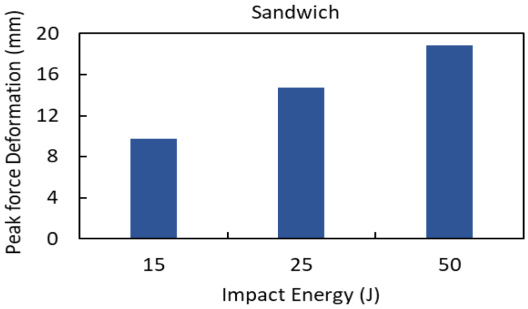

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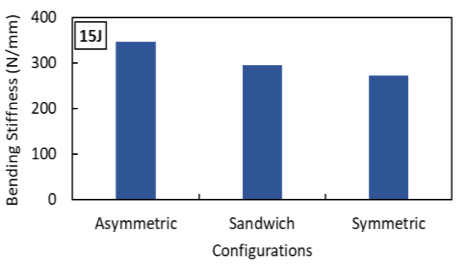
Figure 10. Comparison between peak force deformation-energy of all three combinations at each impact energy.

As the impact energy increases, the bending stiffness may decrease. How difficult it is to bend or flex a material or structure is referred to as its "bending stiffness.". Usually, materials that display considerable plastic deformation or damage in response to high-energy impacts exhibit this behavior. In our case Asymmetric configuration has the highest bending stiffness value over all 3 energies which shows that asymmetric configuration has more strength over symmetric and sandwich.



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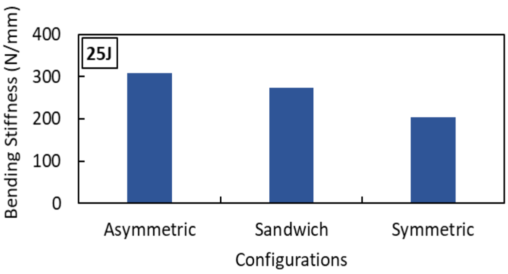

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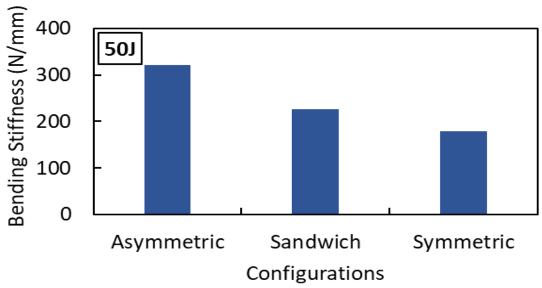

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Figure 11. Comparison between bending stiffness-energy of all three combinations at each impact energy.

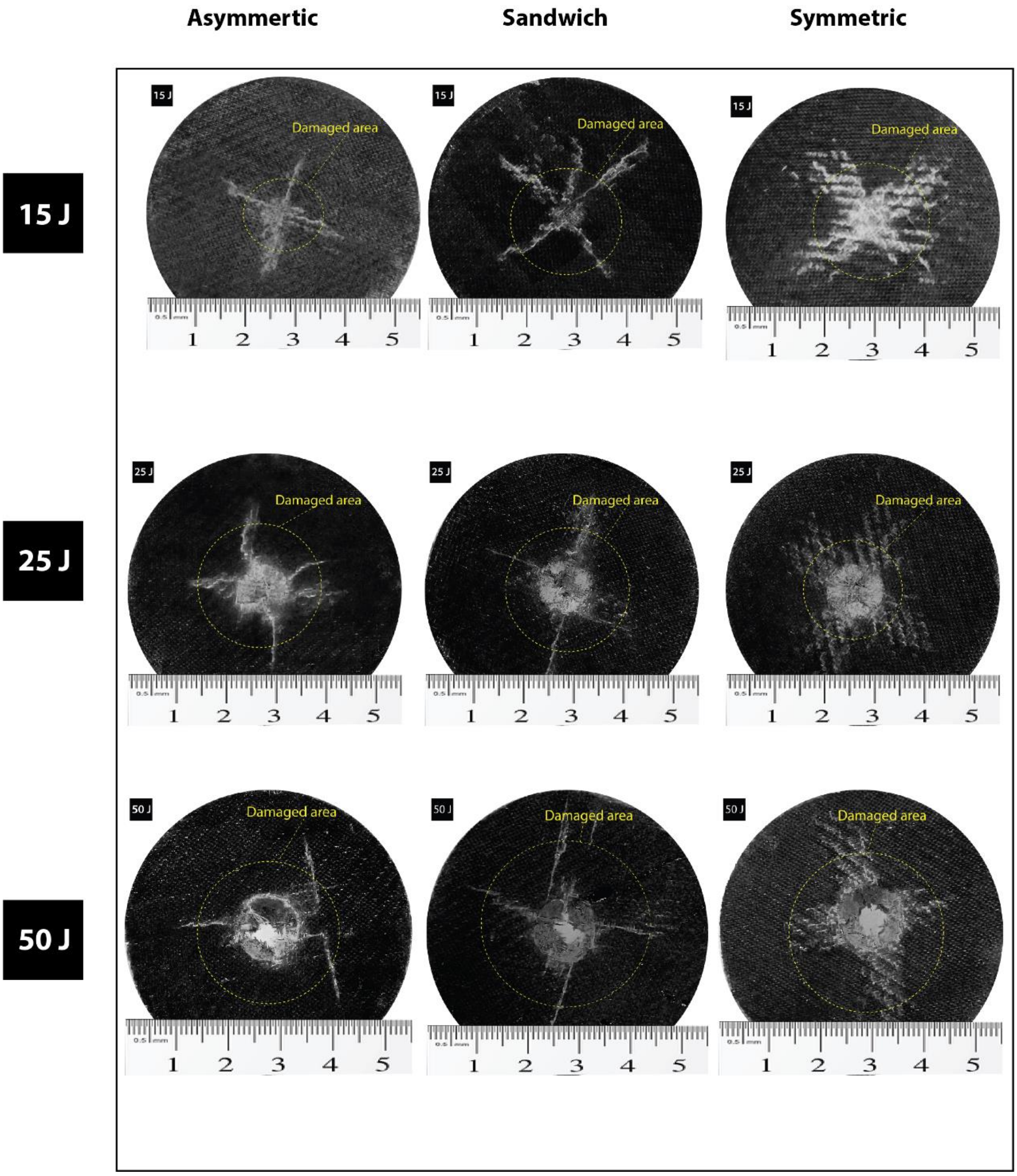
Table 4. Summarized results of single low-velocity impact test of all three configurations of basalt/flax composites at 15J,25J and 50J.

Material	Impact energy (J)	Max force (kN)	Deformation at peak force (mm)	Max. Deformation (mm)
3D-Asymmetric	15	3.06	8.84	9.16
	25	3.55	11.50	15.7
	50	4.41	13.75	24.5
3D- Symmetric	15	2.80	10.30	10.8
	25	2.85	13.38	23.23
	50	3.02	16.92	34.3
3D-Sandwich	15	2.88	9.75	10.29
	25	3.28	11.6	19.78
	50	3.37	14.8	26.7

4.1.3. Impact resistance of 3D-FRC under single impact

Impact resistance of FRC is a major consideration in the design and maintenance of composite constructions. The permanent indentation depth and damaged area in FRC at a certain impact energy are used to calculate impact resistance. In order to assess the impact resistance of FRC, the damaged area and indentation depth were analyzed and compared in this work. As the impact energy increases the damaged area increases as shown in **fig 12.** The symmetric basalt/flax FRC has significantly larger damaged area as compared to other two FRC.

Permanent indentation, along with delamination and fiber splitting/peeling, is one of the key energy-absorbing processes in FRC. Delamination, local fiber failure, and matrix plastic deformation occur as a result of the indentation at or close to the damaged area. It's crucial to measure the depth of the impact-caused indentation to determine the amount of the damage. The indentation depth grows along with the incident impact energy, as shown by all three combinations.



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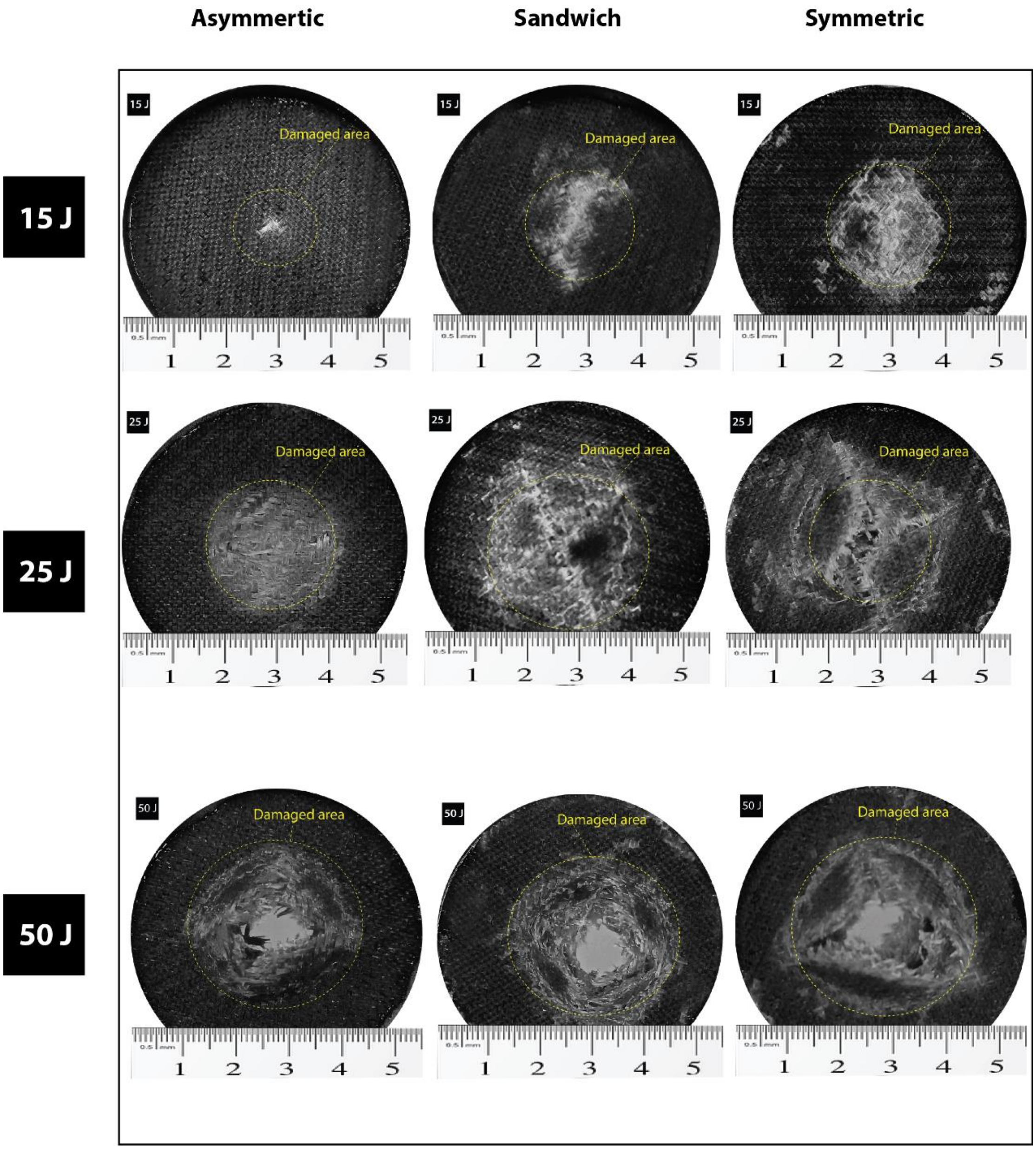


(b)

Figure 12(a&b). Comparison of damage area of impact and non-impact face in Asymmetric, Sandwich and Symmetric 3D composites at 15 J, 25 J, and 50 J. The yellow circles represent damage areas.

4.1.4. Characterization of damage caused by a single low-velocity impact

Comparison of damages occurred at impact and non-impact face of all three FRCs at 15J, 25J and 50J are shown in fig.12. The images clearly show the damage caused by the specimen's deformation on the non-impact face, as well as the indentor's permanent indentation on the impact face. When compared to Symmetric and Sandwich combinations, the damage patterns in Asymmetric basalt/flax-based FRC display reduced damage at all three energies. The damage is classified into two types: micro-damage and macro-damage. Fiber breakage, matrix cracking, and plasticization are examples of micro-damage, whereas permanent indentation, debonding, and yarn straining are examples of macro-damage. Both of these types of damage processes were seen in low velocity impact tests, as shown in the table.

Table 5. Comparison of micro and macroscopic damages.

Material	Damage scale	Damage mechanisms	Case-1 (15 J)	Case-2 (25 J)	Case-3 (50 J)
3D-Asymmetric	Micro damage	Fiber breakage	None	Some	Significant
		Indentation	Some	Moderate	Significant
		Matrix cracking	Some	Moderate	Significant
	Macro damage	Yarn debonding	None	Some	-------------
		Surface VID	BV	BV > (Case 1)	-------------
3D-Symmetric	Micro damage	Fiber breakage	Some	Moderate	Significant
		Indentation	Some	Moderate	Significant
		Matrix cracking	Moderate	Significant	Significant
	Macro damage	Yarn debonding	Some	Significant	------------
		Surface VID	BV	CV> (Sy & Sw)	-------------
3D-Sandwich	Micro damage	Fiber breakage	Some	Moderate(<symmetric)	Significant
		Indentation	Some	Moderate	Significant
		Matrix cracking	Moderate	Moderate	Significant
	Macro damage	Yarn debonding	None	Moderate	-------------
		Surface VID	BV	CV>(Asy)	-------------

The indentor causes local deformation when it contacts the surface, leaving a permanent indentation on the specimen's surface. The velocity of projectile and its mass affect the indentation's depth. The matrix toughness affects how severe the microdamage is.

In case of symmetric configuration, it creates significant amount of matrix cracking and large fiber yarn debonding than other two. Table summarizes the results and highlights that as the velocity increases the indentation depth increases. The indentation caused yarn to fail along with crack propagation.

Fig.13. shows the specimens back face (non-impact face) after being impacted at 15J, 25J and 50J energies. The height(extension) of the damaged zone is measured using the side view of picture. It is evident from the extension pattern that the damage extension increases as the impact energy increases. The Asymmetric and Sandwich configurations have shown almost the same damage extension with very less difference at all three energies; however, at 25J, the Symmetric when compared with Asymmetric has shown considerably less damage extension.

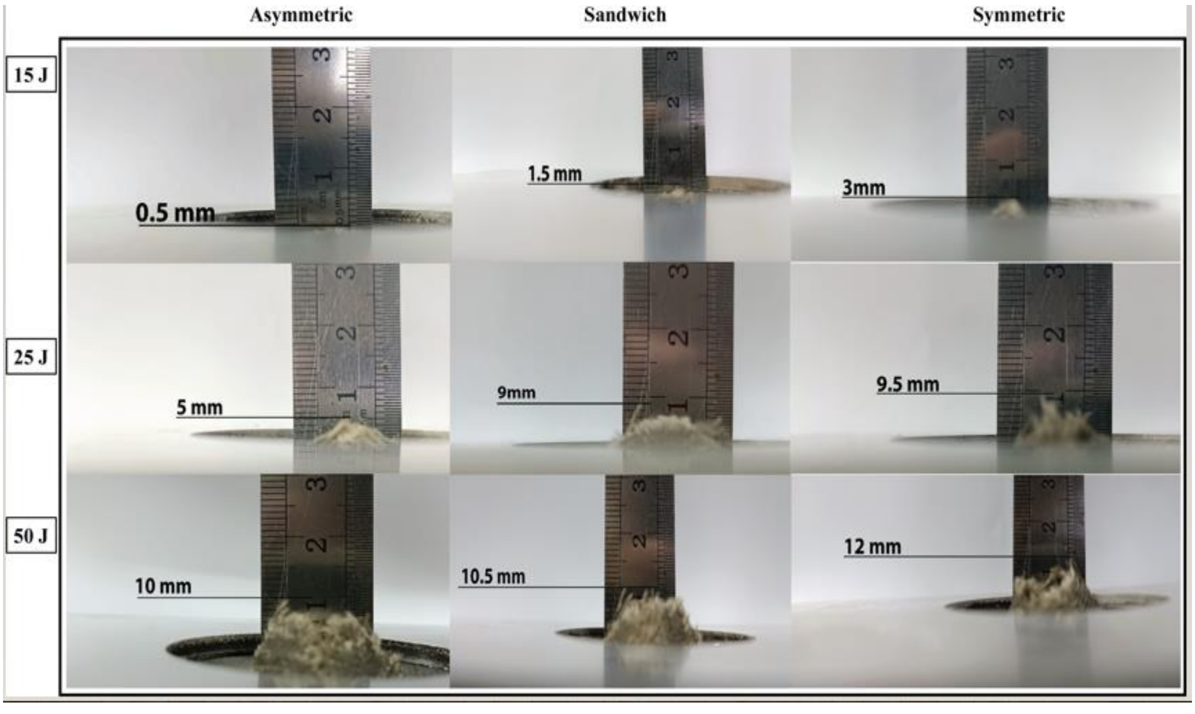
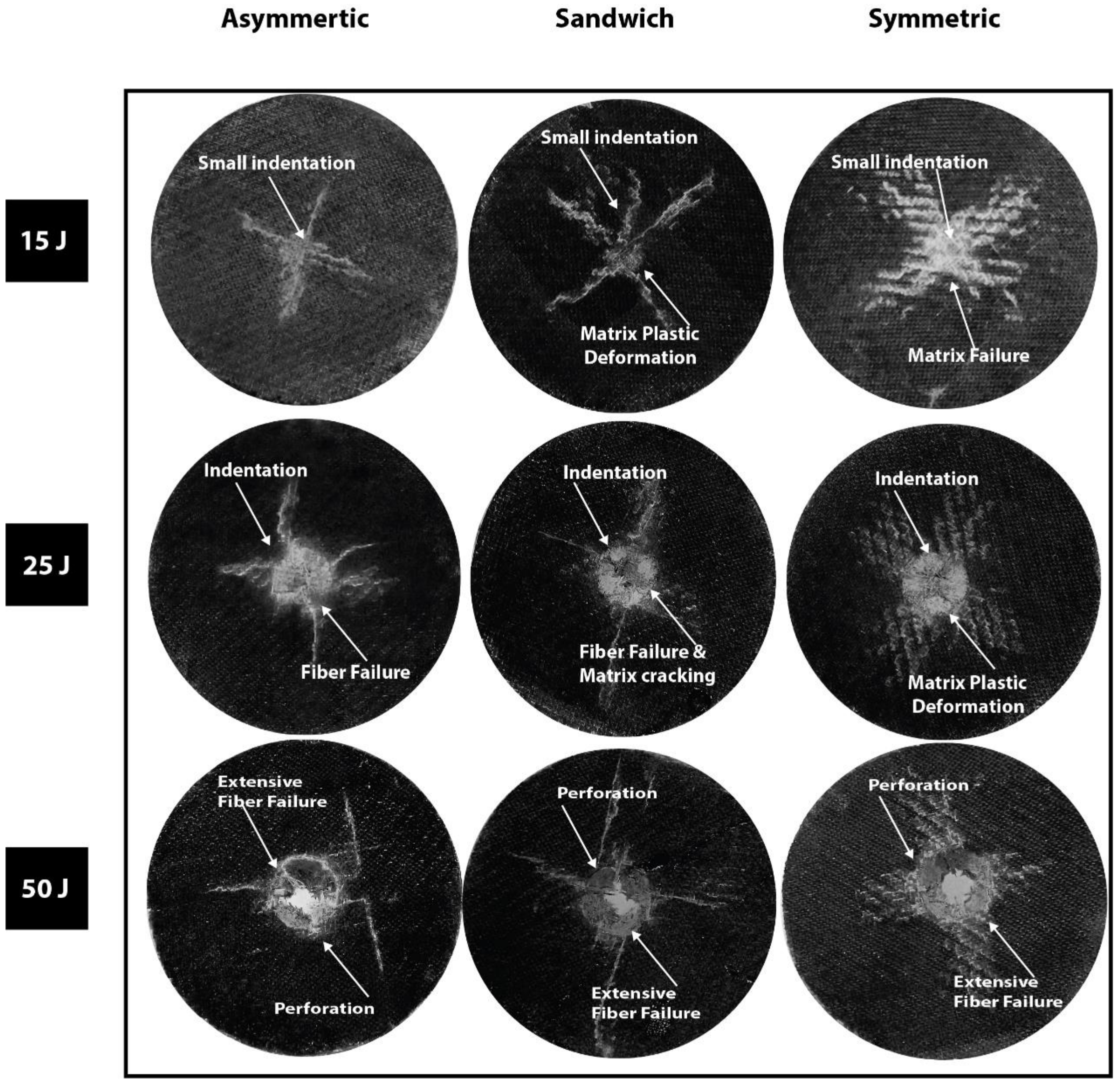
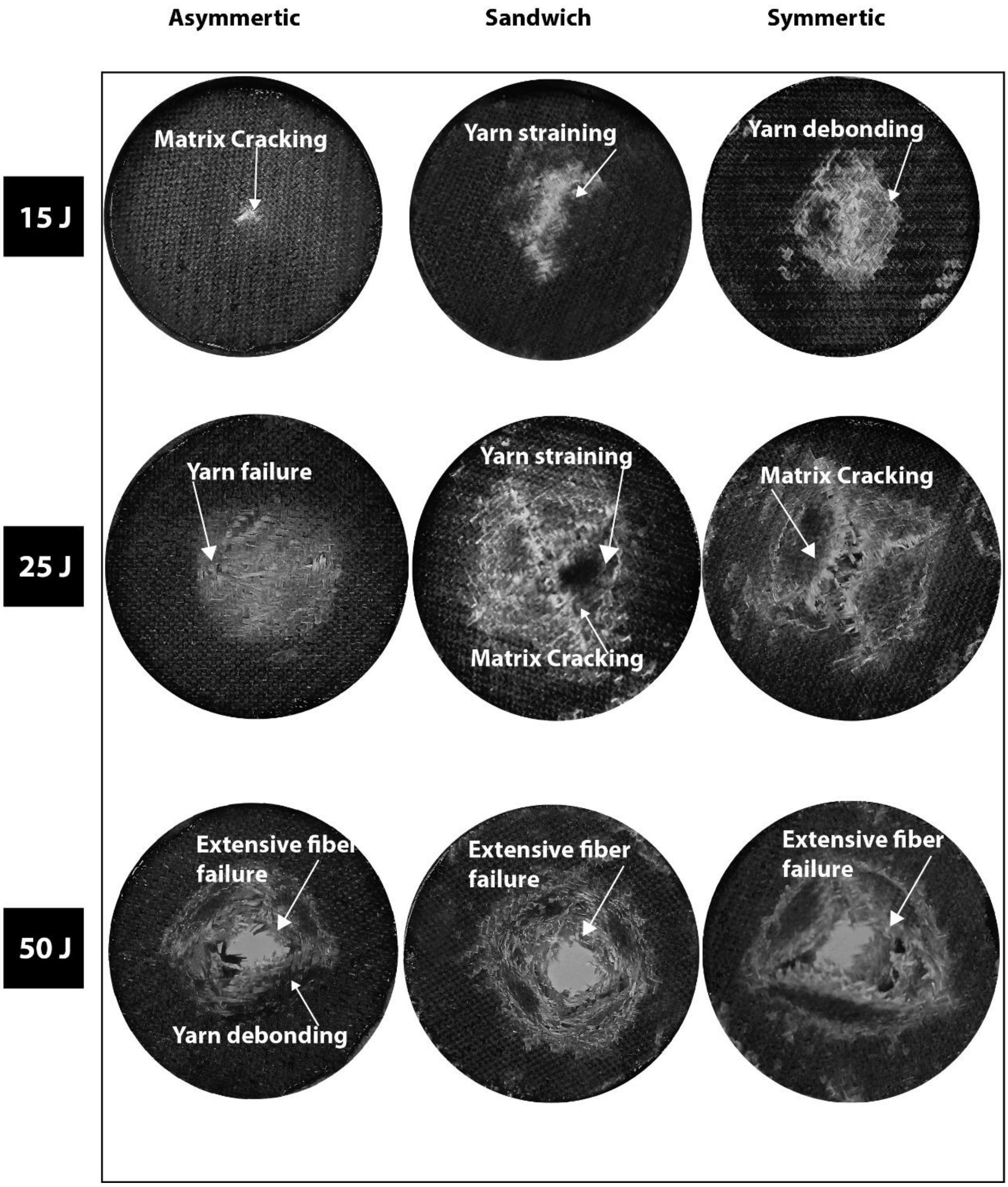


Figure 13. Comparison of damage extension at the non-impact face of Asymmetric, Sandwich and Symmetric basalt/flax 3D composites at 15J,25J and 50J energies.



Asymmertic
Sandwich
Symmetric
15 J
25 J
50 J
Small indentation
Small indentation
Matrix Plastic Deformation
Small indentation
Matrix Failure
Indentation
Fiber Failure
Indentation
Fiber Failure & Matrix cracking
Indentation
Matrix Plastic Deformation
Extensive Fiber Failure
Perforation
Perforation
Extensive Fiber Failure
Perforation
Extensive Fiber Failure

(a)



(b)

Figure 14(a&b). Comparison of macroscopic damage at the impact and non-impact face of the Asymmetric, Symmetric and Sandwich Basalt/flax 3D composite under low velocity impact test. The damage is compared at different impact energies, i.e., 15J, 25 J, 50J.

5. CONCLUSION

In this study, the impact performance of basalt/flax asymmetric, symmetric and sandwich configurations was investigated under a single strike impact and were than compared. From the experimental study, the below mentioned conclusion can be drawn:

- Asymmetric configuration has more force bearing capacity at all energies, i.e., in case of 15J asymmetric withstands 9.5% more force than symmetric and 6.3% more force than sandwich.
- Asymmetric has faced less indentation than symmetric and sandwich at all energies, i.e., in case of 15J the indentation caused in asymmetric is 25% less than symmetric and 6.3% less than sandwich.
- With respect to bending stiffness, Asymmetric has the more bending stiffness which means it has more strength.
- At 50J, the main damage patterns in asymmetric FRC were indentations (perforation) and fiber failures on the impact surface of the sample; while matrix cracking, yarn detachments and significant fiber tears were observed on the back side.

These results showed that the asymmetric FRC had significantly higher impact resistance and less loss of structural integrity in a single impact. This suggests that the FRC based asymmetric basalt/flax configuration is a suitable replacement for asymmetric and layered FRC for many manufacturing industries which use composites.

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