Low Velocity Impact Response of Composite Sandwich Structure with Hybrid Honeycomb Core

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(2024)

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in
Mechanical Engineering

Supervisor: Dr. Aamir Mubashar

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(2024)

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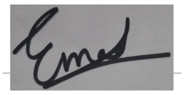
Signature (HOD): 

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DEDICATION

Dedicated to my wife, Sarah, for her endless love, encouragement and support and to my newly born daughter, Humna, for bringing overwhelming joy to my life.

ACKNOWLEDGEMENTS

I am thankful to Allah Almighty, for guiding me throughout this work and opening new ways for me to complete this thesis. Indeed, everything is a special Mercy from You and I am eternally grateful to You.

I am profusely thankful to my beloved parents, whose prayers and words of encouragement have been a source of strength for me. I am also grateful to my loving siblings for their constant support.

I am really thankful to Dr. Aamir Mubashar, under whose supervision this study has been completed. I acknowledge and appreciate his guidance and valuable suggestions.

I would also like to thank Dr. Sadaqat Ali and Dr. Emad Ud Din for being on my thesis guidance and evaluation committee.

I would also like to express appreciation for Mr. Manzar Masud and Mr. Muhammad Saad for their valuable help and cooperation, whenever required for completion of this research work.

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ABSTRACT

Lightweight design is one of the key characteristics of engineering design, as light weight not only reduces operational cost but also reduces the impact on environment due to lesser fuel consumption. The use of sandwich structures is an important advancement in this regard, as sandwich structures use geometrically efficient design to reduce weight and offer superior properties like increased specific strength and stiffness, better fatigue and impact resistance, thermal conductivity and corrosion resistance as compared to their metallic counterparts. Sandwich structures, specifically with honeycomb core and fiber reinforced composite face sheets have been extensively used in aerospace, ship building, rail industry, military and auto motives. Impact loading, especially low velocity impact, is one of the most critical loading scenario for sandwich structures, as impact can cause strength degradation and barely visible damage, which can compromise the structural integrity. In recent times, most of the research has focused on improving the impact resistance of honeycomb sandwich structures by filling honeycomb with a filler material because the porous structure of honeycomb cells is the weakest region against impact loads, especially against oblique impact. This research also focuses on improving the impact resistance of conventional honeycomb by addition of aluminum grid and foam in honeycomb (HC) to produce a hybrid honeycomb (HHC) core sandwich panel. Impact tests are carried out using drop weight method at 30J and 45J for both conventional HC and HHC core and results are recorded in the form of force-displacement, force-time and energy time-response. The testing shows that HHC sustained higher peak force and lower displacement as compared to conventional HC core. The performance index, which compares the performance of HHC with conventional HC, for HHC-foam impact was 1.31 and 1.26 times for 30J and 45J respectively while for HHC-grid impact was 1.14 and 1.16 times for 30J and 45J respectively, highlighting the improved impact resistance of HHC core sandwich panels. Damage characterization through macroscopic damage analysis for damage on surface as well as internal damage was also performed highlighting the various damage modes like delamination, matrix cracking, core crushing and core buckling among other.

Keywords: Light Weight Design, Sandwich Panels, Hybrid Honeycomb, Grid Structure, Drop Weight Impact, Delamination, Core Crushing

CHAPTER 1: INTRODUCTION

1.1 The Need for Lightweight Design

A key attribute that engineers and designers strive for when fabricating various structures and components is lightweight. Lightweight structures offer numerous advantages in various applications. Common examples include aircraft, cars, and ships. A lighter vehicle requires less energy to move, which leads to lower fuel consumption. This reduction in fuel usage not only lessens environmental impact but also decreases the operational costs of the vehicle. One approach to designing lightweight structures is to develop new materials, such as advanced polymer materials or metal alloys with improved properties over existing ones. However, this process tends to be both expensive and time-consuming. Another way for achieving the light weight structures is to use composite structures.

Composite material consists of two or more components combined at macroscopic level to enhance the material properties and serve a design purpose that the individual materials are incapable of fulfilling alone. The two components include a matrix (continuous) and a reinforcing material (fiber, flakes or particles). Composite materials offer superior properties like increased specific strength and stiffness, better fatigue and impact resistance, thermal properties and corrosion resistance as compared to their metallic counterparts. Further, composite materials allow the flexibility to tailor the material according to the application needs, since the fibers can be reoriented to cater for the load carrying need in any specific direction. One of the earliest forms of composites is bricks made up of clay and reinforced with straw. Since 1970s, there has been a progressive increase in the applications of composites due to development of different reinforcing materials like carbon, boron, silica etc. and matrices such as metals and ceramics. Various applications of composites include aerospace structures, automotive, turbine blades, sports equipment and ship components among many others.

1.2 Sandwich Structures

Another advancement in development of structural materials has been the use of sandwich structures. Sandwich structures provide an alternate way to improve the flexure stiffness and strength of material by designing geometrically efficient structures. Sandwich panels are made up of thin, rigid face sheets for stiffness and strength and a light-weight, soft core to resist compression and shear. The purpose of core material is to separate the facesheets and transfer the loads between them. This concept is akin to that of an I-beam, known for its weight efficiency, with the primary difference being that the sandwich structure is continuous.

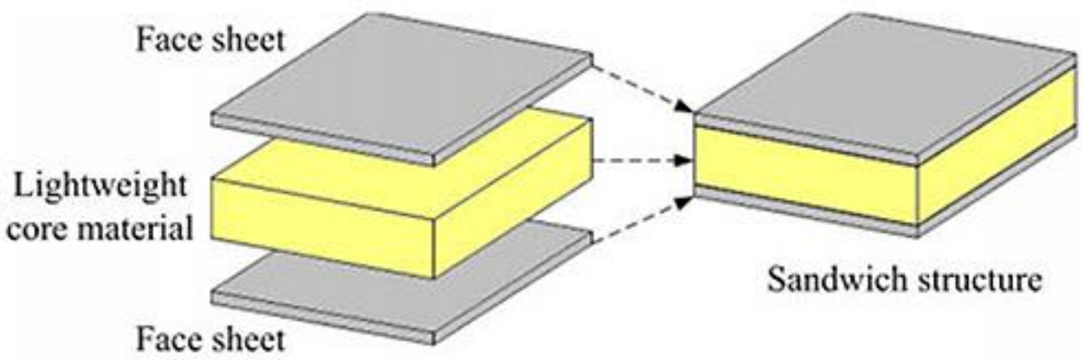

Figure 1.1: Typical Sandwich Structure

Composite materials, with their excellent properties, serve as an excellent option for face sheets while core is generally a lightweight and porous structure. Common types of cores include solid cores, such as polystyrene and polyurethane foam, which can be either rigid or flexible depending on their intended use. Other types of core include honeycomb, truss and web shaped cores. Selection of core is pivotal in determining the transverse shear stress of structure. Sandwich structures, specifically with honeycomb core and composite facesheets have been widely used in aerospace, ship building, rail-industry, military and auto motives because of their exceptional energy absorption, impact resistance and weight reduction capabilities. The use of sandwich panels with honeycomb core transformed the aerospace industry over 40 years ago, resulting in lighter, stronger, and faster aircrafts. This innovation allowed aircraft to improve fuel efficiency and carry more payload. A significant share of the aerospace vehicles is constructed using sandwich panels with honeycomb. Naval ships also employs sandwich panel bulkheads to make ships lighter, helping them stay above the waterline. Additionally, sandwich panels with foam cores is widely utilized in the building of hull of recreational boats.

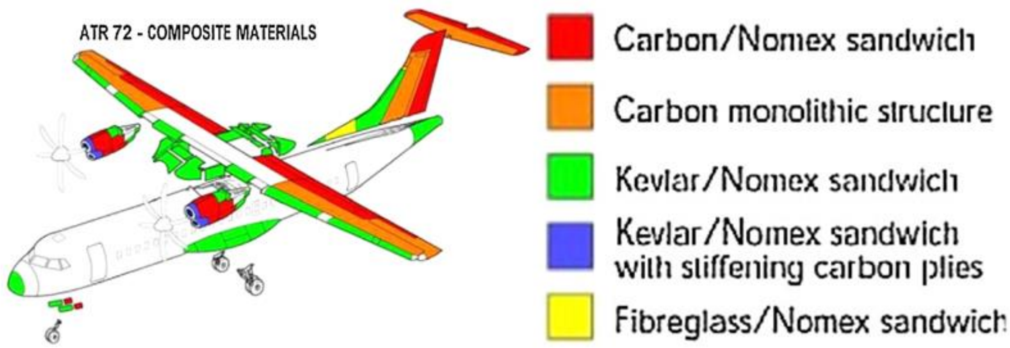

Figure 1.2: Use of Sandwich Structures in Airplane

While sandwich structures have demonstrated high efficiency in withstanding both dynamic and static loads, they still exhibit vulnerability to impacts. Impact damage substantially lowers the load bearing ability of sandwich structure, and ultimately results in failure of structure. Therefore, study of different damage modes like delamination, fiber fracture, matrix cracking, core breaking and even perforation (under high energy impact) is of paramount importance for the structural integrity of structure.

1.3 Impact in Sandwich Structures

Sandwich structures are extremely prone to impact loads and show poor resistance against impact loads. This characteristic results in degradation of material properties after impact and adversely effects the load bearing capacity. Mainly impact events are studied under two categories: Low-velocity-impact (LVI) loads and high-velocity-impact (HVI) loads. Impacts at velocity < 10 m/s are categorized as LVI. Impacts can also be classified as soft impact and hard impact. Bird strikes are a common example of soft body impacts, while hail storms and impacts from runway debris represent hard body impacts. These impact scenarios pose significant threats to flight safety and result in substantial costs for the aviation industry. Bird strikes alone cost the aviation industry over 1 billion USD annually [1].

Figure 1.3: Bird Strike on an Aircraft

Micro damages typically known as BVID (barely visible impact damage) have more chances of appearing in low energy impact events as compared to high-energy impact loads, but can prove fatal to bending load bearing capability and safety of structure. Therefore, LVI is a potentially catastrophic phenomenon as the damage in this case can left unnoticed.

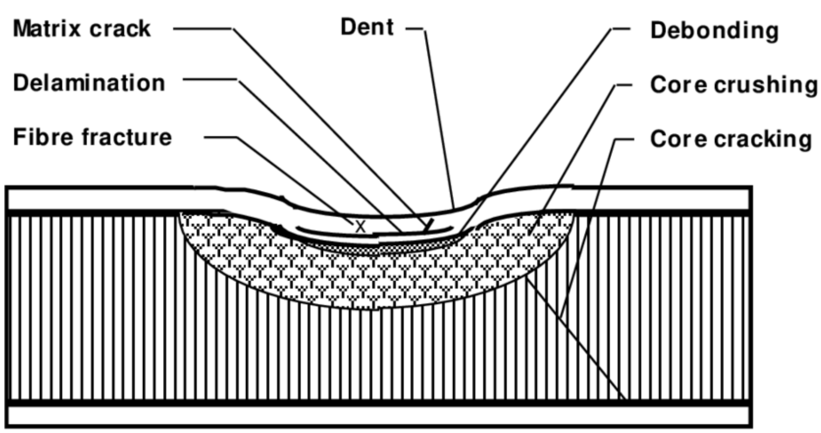

Figure 1.4: Impact on Sandwich Structures

Hail stone, tool drop, bird-strike and runway debris, etc are different sources which can result in LVI. Various damage modes can develop depending on the energy of impactor. These modes include delamination of facesheets, de-bonding of skin with core, core-crushing and shear, matrix cracking, and fiber damage and core buckling. [2].

Delamination is a commonly observed failure mechanism in sandwich structures with fiber-based composites due to their comparatively low inter-laminar strength. This mode of damage can occur in various scenarios, notably for the case of low-velocity transverse impacts. Consequently, much of the ongoing research concerning sandwich panels is geared towards enhancing their impact resistance through optimization of material selection and mechanical properties for better absorption of impact energy.

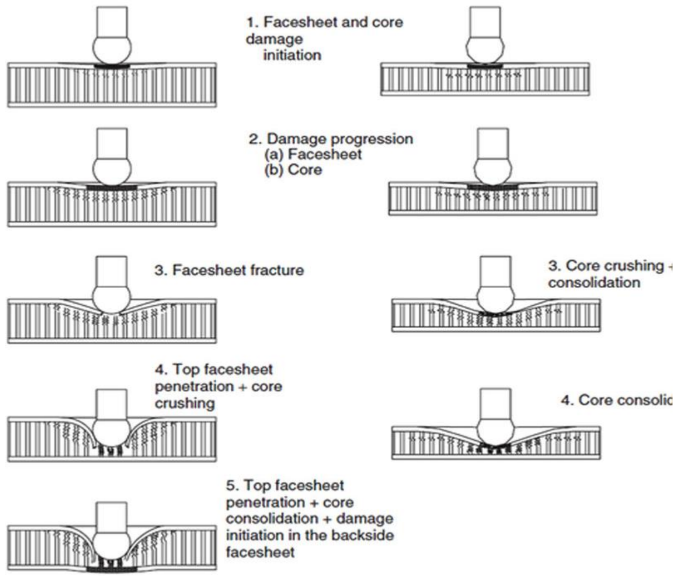

Figure 1.5: Damage Modes in Sandwich Structures

CHAPTER 2: LITERATURE REVIEW

An impact load can be defined as a sudden and transient force applied to a structure. This type of force occurs over a very short time and can result in abrupt changes in stress and deformations. Impact loads are generally the result of dynamic events such as explosions and collisions. Impact strength of a material is the measure of its ability to absorb energy and resist fracture under impact-load. This critical property determines the material's capability to withstand cracks and plastic deformation.

The American Society for Testing and Materials (ASTM) defines sandwich structures as a combination of different material that are bonded together to create a structural advantage through combination of properties of individual materials. Sandwich structure maximizes the advantages of conventional materials alongside the superb energy absorption features of cellular cores. By capitalizing on their strengths and addressing their limitations, this combinations provides a promising material design. Sandwich panels have been widely used in many engineering fields including aircrafts, satellites, boats etc. They are especially being utilized in aviation, military and auto-motive industries because of their higher stiffness, strength, low density and designability. Keeping in view these qualities, an expansion happened in the utilization of sandwich panels in vast range of applications. Hence, it is very crucial to study the mechanical behavior of sandwich panels and their corresponding damage modes under various loading scenarios.

Impact event happens to be one such critical loading condition, which is a critical phenomenon as it includes a very intricate stress dispersion in the material, e.g. compression being maximum at top surface, tension at bottom surface, shear stress at the interface of facesheet and core and stress at contact point just behind the projectile. Despite their exceptional advantages, sandwich structures are quite vulnerable to impact loads. Such load can cause internal damage, which can significantly reduce their structural strength and stiffness, even if it is undetectable or barely noticeable upon visual inspection [3], [4]. Hence, behavior of sandwich structures under dyanmic loading gained much attention in last few years. Anisotropic and inhomogeneous nature of sandwich panels due to combination of different materials made the analysis of damage modes and failure complex and difficult to investigate. Since impact damages are inevitable and unavoidable, it is crucial to study them. Improving the energy-absorbing capabilities and impact performance of sandwich panels is essential to prevent catastrophic structural failure. Therefore, the dynamic response of sandwich structures under high strain rate loading has been studied in great detail experimentally, numerically and analytically. One of the concern in enhancing the performance of composites used as structural materials under impact loading is understanding their characteristics and examining their energy dissipation capacity under impact loads.

2.1 Historical Background

The concept of sandwich structures has been used since ancient times, although in different forms. In architecture, arches and walls were strengthened and insulated by using materials like mud or clay between layers of stone or bricks. A prominent example of sandwich structures in engineering dates back to World War II, namely in aircraft design. To increase performance and fuel economy, aircraft designers looked for materials that were both strong and lightweight. Sandwich constructions, with two layers of stronger materials encasing a lighter core material, proved to be a very successful design. By reducing weight, this design increased the strength-to-weight ratio of aircraft parts, increasing their robustness. With advancements in materials science and manufacturing techniques, engineers began experimenting with different materials for core such as honeycomb, foam and balsa wood, combined with metal or composite face sheets. Sandwich panels have been in use for a long time and an extensive work has been conducted on it.

Different configuration of sandwich panels can be used like single layer sandwich panel or multiple layer sandwich panel depending upon the application requirement [5]. The impact event for a body can be categorized into various subgroups with respect to the impact velocity i.e., low, medium and ballistic impact velocity events. Various researches have marked different ranges for impact velocity regimes. According to literature [6], velocity less than 20m/s is qualified as a low velocity loading. Later on, another classification was presented and it defined the low velocity below 100 m/s [7]. Other investigations have associated the high velocity regime of the impact load with perforation of the sandwich panel and is mainly caused by runaway debris, turbine blades and broken engine parts in aerospace applications [8]. Aside from impact velocity, impactor's mass is an essential factor to be considered while investigating the impact response. Research is also available on the mass ratio criterion that determines whether the quasi-static deformation is appropriate to assume [9].

2.2 Face sheet Materials

One of the dominant feature in the study of impact is the material of fibers and matrix. The most frequently utilized fiber types for facesheet include glass and carbon fibers. A comprehensive study on the impact response of sandwich composites was conducted, particularly emphasizing the influence of facesheet materials [10]. LVI responses of sandwich composites with various face sheet materials with rigid polyurethane core was studied. The materials used for face sheets included glass, woven carbon, Carbon / Kevlar, and Kevlar fabrics. The experimental findings revealed that Kevlar reinforced face sheets exhibited the smallest crack and indentation in comparison with other fibers. The impact behavior of sandwich composites with GFRP and CFRP facesheets was compared by Ugale et al [11]. Penetration occurred in specimen with GFRP face sheet at 18 J while the specimen with CFRP facesheet did not experience penetration due to the higher elastic deflection of material. Another comparative study on CFRP and GFRP face sheets by Yang et al [12] revealed that residual compression after-impact strength reduced significantly greater for sandwich composites with CFRP skins compared to those with GFRP skins..

Xie et al inspected the effect of facesheet thickness and core density of sandwich structure comprising of Aluminum 5052 facesheet and Nomex honeycomb core under dynamic load[13]. The results of the investigation showed that, in comparison to increasing the core density, increasing the thickness of the face sheet greatly enhanced the impact resistance. LVI testing, performed to assess the effect of structural parameters, revealed that the thickness of facesheet greatly influences the impact performance [14]. Honeycomb call wall thickness and length also effect impact load while height has very little effect. For low velocity impacts, the most frequent failure types include delamination and matrix cracking.

2.3 Core Materials

The selection of core of a sandwich structures is very significant as it has a substantial effect on the impact behavior and energy absorption capability of sandwich composite. The most commonly used core include foam, honeycomb, corrugated, truss, and auxetic, balsa wood and cork among others.

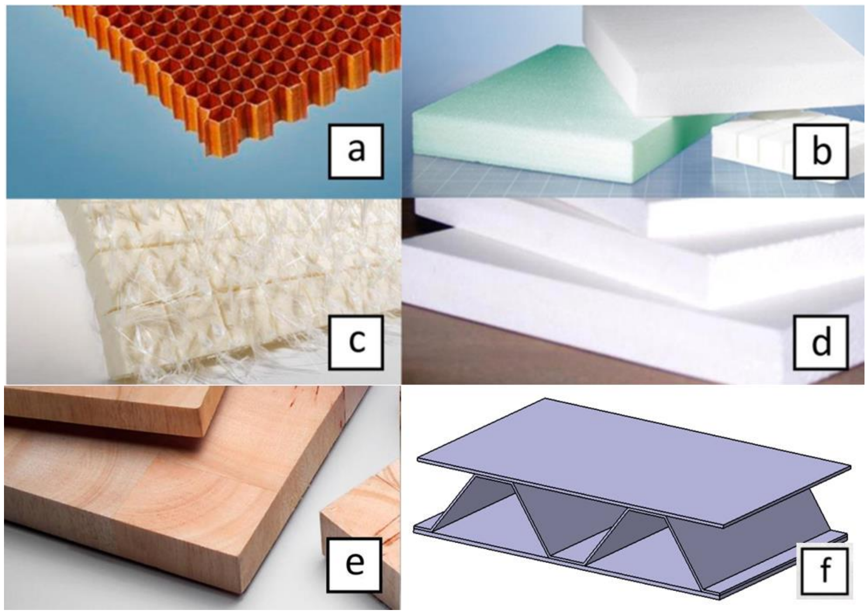

Figure 2.1: Different Core Materials a) Honeycomb, b) Foam, c) Fiber reinforced SAN Foam, d) PVC Foam, e) Balsa Wood, f) Corrugated Core

Polyurethane foam is one of the most frequently utilized core materials because of its lightweight, good strength and energy absorbing capabilities. It has a wide range of applications, from aircraft interiors to car doors and boat hulls. PU foam is produced through a chemical reaction between polyol and isocyanate, in the presence of a blowing agent which gives the foam its structure. The findings of the steel plate – polyurethane foam composite structure's static compression testing showed that the completely filled foam specimen had far higher crushing force efficiency and energy absorption. Additionally, energy performance of PU foam is improved by increasing its density [15].

Aluminum foam is typically manufactured by introducing gas or foaming agents into molten aluminum. This results in a porous structure that retains the light weight nature of aluminum while preserving its strength and durability. When subjected to compression, aluminum foam can deform significantly under nearly constant force or stress, showcasing impressive energy absorption capabilities. The impact performance of an aluminum foam core with different facesheets revealed that a thicker foam has a higher capacity for energy absorption. [16]. The analysis of aluminum foam sandwich structures subjected to LVI was conducted to evaluate the dynamic behaviors, damage, deformation and energy absorption. The study found that increasing the core density of sandwich structure enhanced its stiffness and that a higher core density is beneficial in preventing perforation [17].

The honeycomb structure consists of interconnected hexagonal cells, having internal space and resulting in a lightweight yet highly rigid structure. This configuration offers impressive strength to weight ratio and robustness and it can also withstand significant deformation in the normal direction. This structural design is not only prevalent in engineering but also commonly found in nature [18], exemplified by the honeycomb constructed by bees or turtle shells. With their exceptional performance characteristics, honeycomb structures are increasingly finding applications across various engineering domains. Consequently, honeycomb sandwich structures have seen widespread use, with extensive studies on their impact resistance. In order to comprehend the implications of structural factors on impact resistance, research has centered on aspects including face sheet thickness, height, edge length, and honeycomb wall thickness. [19], [20], [21]. Honeycomb structures typically consist of metallic or composite facesheets paired with aluminum or Nomex honeycomb cores. The geometric characteristics of these sandwich structures, such as the height of the honeycomb core, face sheet's thickness, and the cell length, may be utilized to characterize them. Although multiple studies have been done on the damage characteristics and impact of honeycomb sandwich constructions, most of them have centered on aluminum materials. Foo et al. investigated the effect of foil thickness and cell size of the honeycomb [22]. They found that the impact response was influenced by the honeycomb core density. Crupi et al. examined the LVI behaviors and static three-point bending of aluminum honeycomb sandwich constructions, emphasizing on the influence of cell size. [23].

Corrugated shaped sandwich cores can be categorized into various types such as trapezoidal, triangular, sinusoidal, cap-shaped and diamond-shaped based on their topological configuration. Triangular corrugated sandwich structures primarily experience tensile or compressive deformation rather than bending under small deformations. This characteristic gives them the ability to withstand significant compressive or tensile stresses [24]. Trapezoidal corrugated sandwich structures find widespread use in constructing vehicle bodies and chassis. This design improves the vehicle's stiffness and impact resistance while reducing noise and vibration effects for passengers. Likewise, in aviation, the wings are strengthened and stiffened with the use of trapezoidal corrugated sandwich structures, which reduces the force of aerodynamic stresses on the aircraft.

2.4 Improving Impact Resistance

A number of techniques have been found to improve sandwich structure's ability to support loads and energy absorption. Zhang et al. demonstrated that superior results were obtained by thickening the top face sheet while keeping the total thickness of top and bottom facesheets same. [25]. Another study by Sun et al [26] concluded that inserting short aramid fibers at the interface of core and face sheet improved the energy absorption capabilities while different studies show that increasing the foam core density also improves the loadbearing. Another way to increase the impact resistance is the through foam filling along with other cores. Mei et al explored the ballistic impact response of a sandwich panel with X-frame cores as compared to foam filled X-Frame cores using gas gun [27]. The study revealed that filling the lightweight PU foams significantly enhanced the energy absorption capacity. The foams help redistribute the load and results in reduced stress on the bottom face sheet. Wang et al. performed LVI perforation and three point bending studies and used the foam filling to enhance the impact behavior of woven lattice truss panels. [28]. The experiments indicated that filling foam can effectively absorb energy, increase impact resistance and reduce damage to back skin. Hassanpour et al compared the unfilled and PU foam filled honeycomb core panels using gas gun. The dynamic strength and energy absorption was enhanced by foam filling, with the highest ballistic limit achieved for higher density foam [29].

Some studies have focused on adding grid structures to the core materials to improve the impact response. The grid structure offers numerous advantages such as enhanced resistance against buckling, withstands higher loads and ease of design. [30]. Shi et al. performed three-point bending tests by incorporating an ortho-grid structure into sandwich panel to increase the stiffness of the core and reduce mismatch at interface of core and facesheet. The sandwich structure with a honeycomb-filled ortho grid core showed significant enhancements in bending strength as well as energy absorption [31]. Under in-plane compression, sandwich panels with a grid-reinforced honeycomb core were analyzed and compared with structures that had either a honeycomb or a grid core. [32]. The combined core sandwich specimens performed exceptionally well as compared to individual cores and resulted in better impact performance, provided high damage tolerance and prevented both interfacial de-bonding and local buckling of the core. The impact response of grid reinforced panels using drop hammer was studied to investigate impact resistance and damage morphology at different locations. The study revealed that the impact resistance at intersection and rib was more as compared to center location and internal damage was smaller. Additionally, the thickness of grid significantly affected the impact response [33].

Several studies [34], [35], [36] showed the great energy-bearing capability of conventional honeycomb core sandwich panel under impact loads. However, application of honeycomb core panels have strict consideration of weight and size. For example, the sandwich panel used for a vehicle body must be made as a lamina structure due to weight constraints, hence the panel's thickness cannot be increased beyond a certain limit. Under these conditions, the energy absorption and flexural rigidity of a sandwich panel with a conventional honeycomb core are insufficient, and impact loading can cause excessive damage locally. Additionally, oblique impacts, in comparison with vertical impacts, cause extreme local bending of the cell walls and can also result in de-bonding of the adhesive layer of the core due to the hollow areas in the honeycomb cells [37]. The easiest method to enhance the load carrying ability of the panel is to increase the thickness of cell wall. However, thicker cell walls make the core more rigid, resulting in reduced energy absorption capacity. Recently, research has been focusing on improving the local impact resistance of structures. Among them, sandwich panels with auxetic core offer an excellent choice for the local impact load bearing. However, the manufacturing capabilities needed for producing such complex cellular structures are not easily available, resulting in huge costs for engineering applications. Therefore, sandwich panels with composite face sheets and combinations of core materials offer a more economical option.

As discussed earlier, various studies have shown that adding foam further enhances the energy absorption and load bearing capacity of honeycomb while adding grid structure improves the interfacial interaction of soft core material with stiff face sheets resulting in better impact resistance. Therefore, this study offers an alternative design by filling foam in hexagon honeycomb cell and adding grid structure to further improve the response under impact loading. Because of foam filing in honeycomb cells, the interaction occurs in each cells, which gives this configuration the ability for much more energy absorption and improved mechanical performances.

2.5 Problem Statement

Various methods are being employed to enhance the impact performance of honeycomb sandwich-panel. This research focuses on one such method i.e. the addition of foam and grid to honeycomb to produce a hybrid core. LVI loading can cause internal damage and severely affect the properties of sandwich composite structures, despite the damage being barely noticeable by visual inspection and compromise the structural integrity. Consequently, it is important to analyze the LVI behavior and damage characteristics of such structures. The aim of this research is to explore the response of composite sandwich panel with honeycomb core, reinforced with grid and foam under low velocity impact.

2.6 Objectives

The objectives of current research are: and damage mechanism of such structures.

- Manufacture a sandwich panel with composite facesheets and hybrid honeycomb core
- Perform LVI testing of samples at multiple energy levels using drop-weight testing method
- Study the impact response along with various damage modes of sandwich panel

CHAPTER 3: MATERIALS & METHODOLOGY

3.1 Materials

Woven carbon fabric, imported from China and purchased from a local supplier, Pak Fiber, Islamabad, was used to manufacture face sheets. The fabric had a 2 x 2 twill-weave and area density of 200 g/m^2. Properties of the woven carbon fabric are mentioned in **Table 3.1** [39**]**.

Table 3.1: Woven Carbon Fabric – Mechanical Properties

Area Density	200 gsm
Thickness	0.2 mm
Tensile Modulus	E (Weft): 230 GPa, E (Warp): 230 GPa
Tensile Strength	σ_t (Weft) = 3750 MPa, σ_t (Warp) = 3750 MPa
Elongation at Break	ε_f (Weft) = 1.8%, ε_f (Warp) = 1.8%

The resin matrix was a laminating epoxy provided by RIEARO Ltd., catalyzed with a formulated amine hardener from the same supplier. Properties of epoxy used for manufacturing the samples are mentioned in **Table 3.2** [40]. The epoxy and hardener are combined in a weight ratio of 2:1. This resulted in a uniform mixture with a viscosity of 1000–1400 mPa.s at ambient temperature and pot life of roughly 115 min at 25^{o}C, according to the supplier's specification. The chosen resin system, due to its extended working time and viscosity, was suited for fiber impregnation as it strikes a balance between flowability and thickness. NOMEX honeycomb, manufactured with meta-aramid aerospace grade paper and coated with phenolic was used as a core. Properties are mentioned in **Table 3.3** [41]. It has excellent strength despite being lightweight and is commonly used in various applications. It had a density of 48 kg/m^3, 8mm height, cell size of 4.8mm and side length of 2.75mm.

Table 3.2: RAIERO Laminating Epoxy Properties

Parameter		Resin	Hardener	Combined
Uncured	Density (g/cm³)	1.13-1.17	0.90-0.95	1.08-1.12
	Viscosity (mPa.s)	1200-1800	5-20	1000-1400
Cured	Tensile Strength (MPa)	70-80		
	Elongation (%)	6-10		
	Bending-Strength (MPa)	103-117		
	Bending-Modulus (MPa)	2600-3200		
	Hardness (Shore D)	84-88		

Table 3.3: NOMEX Honeycomb Material Properties

Height (mm)	8
Density (kg/m^3)	48
Cell Size (mm)	4.8
Side Length (mm)	2.75
Compressive Strength (Stabilized)	2.4
Shear Strength (L)	1.2
Shear-.Modulus (L)	40
Shear Strength (W)	0.7
Shear Modulus (W)	25
Compressive Modulus (Stabilized)	140

For grid, Aluminum 2219 was used as it is light weight and is easily available. Properties of aluminum are mentioned in **Table 3.4**. PU foam was formulated by combining blowing agent and polyurethane foam [38] by mass-ratio of 1:2 and used to fill the honeycomb cells and together with grid, formed the HHC core for sandwich structure.

Table 3.4: Al 2219 Mechanical Properties

Density (kg/m^3)	Young's Modulus (MPa)	Yield Strength (MPa)
2680	70	250

3.2 Manufacturing Process

The first step in preparation of sandwich panels is the manufacturing of composite face sheets. Carbon fabric was sliced into small pieces of 150mm by 100mm, which is the standard sample size. Vacuum bagging is used to produce all composite face sheets because of its ease and cost effectiveness. The selection of vacuum bagging was based on its compliance with industry norms as well as its unique advantages in guaranteeing process quality and consistency, especially in terms of minimizing void formation in the composite structure. The process starts with applying a release agent to a glass mold using a brush to facilitate the easy removal of the cured composite part. Next, epoxy resin is manually injected into the CFRP using the hand-layup technique, with each face sheet comprising five layers of carbon fabric. This is followed by applying peel ply, perforated film, and breather cloth. The layup is made airtight by using sealing tape around the edges and wrapping it with a vacuum bag. In order to save time, multiple samples are produced in a single vacuum cycle. A representative vacuum-bagging process is shown in **Figure 3.1**. To get the best mechanical properties and avoid any voids, vacuum was kept for ten hours at room temperature.

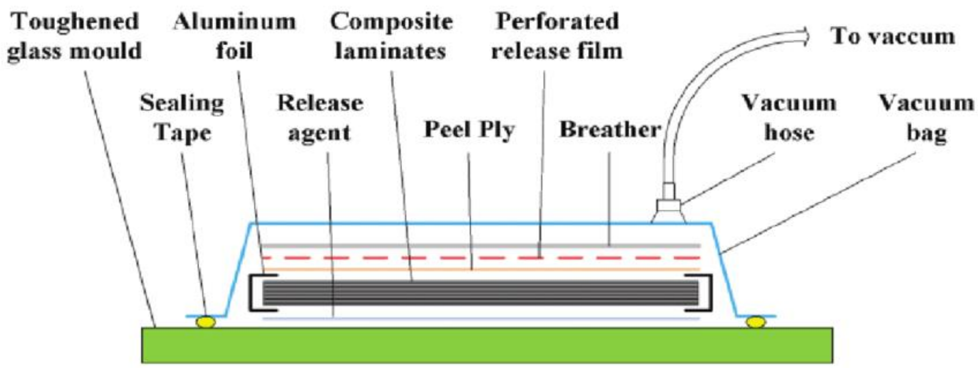

Figure 3.1: Typical Vacuum-Bagging Process

Figure 3.2: Vacuum Bagging Process for Manufacturing Sandwich Panel: a) Cutting Carbon Fabric into Small Pieces, b) Applying Epoxy & Adding Layers, c) Vacuum Creation to Remove Excess Epoxy

Once the face sheets were manufactured, the next step was to make the sandwich panel. Honeycomb was sliced in the standard size of 150 mm x 100 mm before further cutting in small pieces according to grid size. The next step was the foam filling of honeycomb. Once the honeycomb was filled with foam, sandwich panel was produced by combining the individual components. For the adhesively bonding face sheets with HHC core, Huntsman Araldite© 2215-1/A and 2215-1/B epoxy was used. This was done to ensure that a good bond is established between the facesheets and core. Total thickness of sample is 10.4 ± 0.1 mm. Finished sample, along with individual components is shown in **Figure 3.3**.

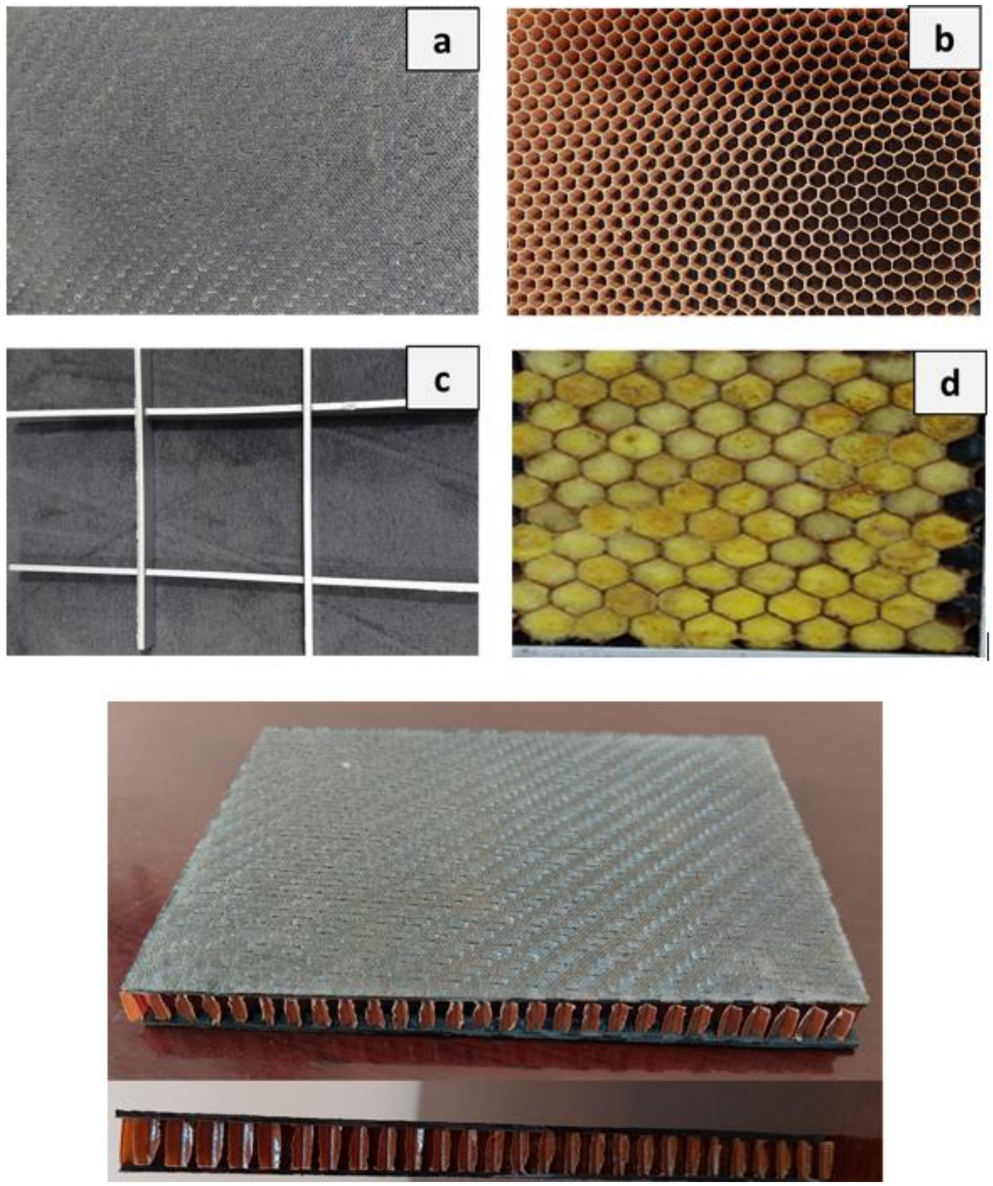

Figure 3.3: Finished Sample along with a) CFRP Facesheet, b) Unfilled Nomex Honeycomb, c) Grid Structure, d) Foam Filled Honeycomb

3.3 Experimental Methodology

Impact tests of structure were performed using drop weight tower machine in accordance with ASTM D7766/D7766M-23, procedure C [42], which is based on ASTM D7136/D7136M-12 [43]. A standard test sample for impact test is shown in **Figure 3.4**. The tests were done using BESMAK drop test tower provided by BESMAK Materials Testing Machines, Turkey. The dimensions of sample are 150 mm x 100 mm. It is secured to the impact testing surface with four clamps, each equipped with rubber dampers at their ends to absorb vibrations generated by the impact.

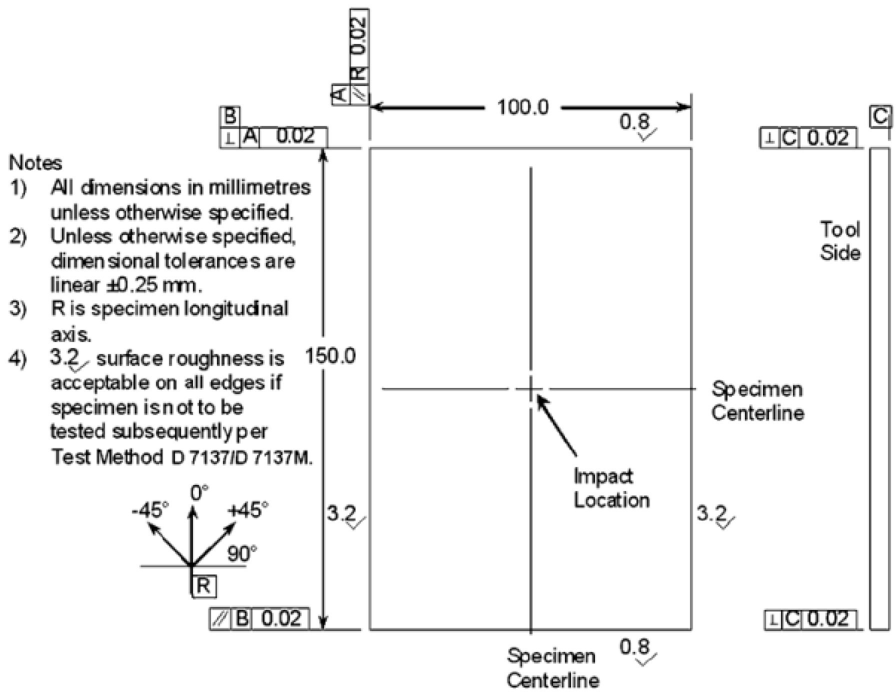

Figure 3.4: Typical Impact Test Specimen

The indenter features a hemi-spherical nose at the end of a cylindrical body. The program determines the initial velocity upon impact, as measured by the optical sensor that is fixed to the test equipment. The carriage and impactor have a combined mass of 5.67 kg, however more mass may be added for a greater impact energy. The overall mass used in all tests was kept constant at 9.67 kg, although the impact energy was changes by varying the drop height.

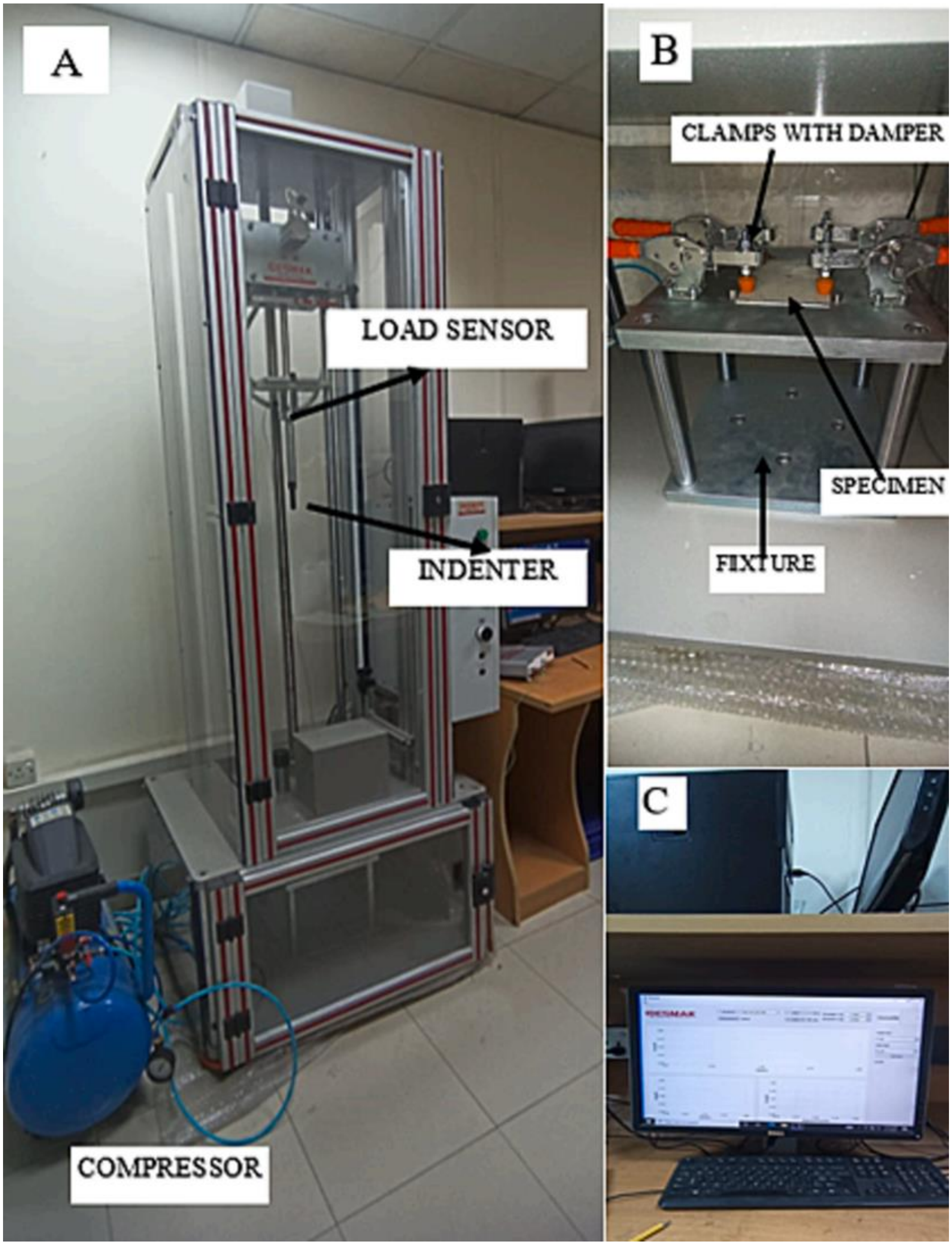

Figure 3.5: BESMAK LVI testing machine. A) Hemispherical indenter, load-cell and compressor, (B) Support fixture (C) The controller

After each experiment, different characteristics, including impact velocity, maximum force, and impact energy, are recorded by the data collecting device. **Table 3.5** lists the various parameters used in impact test. Two types of samples are tested in this research. One is the basic sample which has carbon fabric face sheets with honeycomb core. Second sample is made up of carbon fabric facesheets and HHC core i.e. hybrid honeycomb reinforced with grid and foam. To see the effect of foam and grid, two types of impact tests are performed for second sample. In one experiment, the impact is at foam filled honeycomb location, while in the second experiment, the impact is at the intersection of grid.

Table 3.5: Drop Weight Impact Test Parameters

<table>
<tr><th>Impact Type</th><th>Sample</th><th>Energy (J)</th><th>Velocity (m/s)</th><th>Drop Height (m)</th><th>Drop Mass (kg)</th></tr>
<tr><td rowspan="2">Single Impact</td><td rowspan="2">Conventional Honeycomb Core & HHC Core Panel</td><td>30</td><td>2.505</td><td>0.316</td><td rowspan="2">9.67</td></tr>
<tr><td>45</td><td>3.036</td><td>0.474</td></tr>
</table>

CHAPTER 4: RESULTS & DISCUSSION

The LVI performance of the sandwich panel is evaluated using drop weight impact test and investigated in terms of force vs. time, force vs. deformation, velocity vs. time, displacement vs. time and energy vs. time graphs. The results are discussed in details in the following sections.

4.1 Typical Impact Response

The impact load is the most essential characteristic to measure the structural response and failure phenomenon of impact loading on sandwich structures. During LVI, the structural response can be divided into 3 different categories [14] , namely: rebound (Type A), onset of perforation (Type B), perforation (Type C). The typical force vs. time, force vs. displacement and energy v s. time curves for these three cases are shown in **Figure 4.1**.

Type A, which typically occurs in lower impact energy cases, is characterized by a typical loading profile with a single-peak load, involving ascending and descending phases. This type of behavior is observed when the absorbed or dissipated energy of the test sample is less than the initial impact energy. In this scenario, the impact zone around the upper facesheet primarily experiences local bending and membrane stretching, while the core in this area shows localized crushing and buckling. Additionally, the upper face sheet may have a barely noticeable depression, possibly due to matrix cracking perpendicular to the fiber. When the contact force reaches its peak value, the impactor rebounds, and some of the energy is absorbed through permanent material damage to the top face sheet and honeycomb core, as well as through heat and vibration. The excess impact energy from the drop-weight system is retained in the indenter, causing it to bounce back from the test specimen.

Type B is characterized by a single, extended loading plateau that follows a single peak load. The top facesheet experiences the start of fiber fracture as the load reaches its greatest value; after fiber breakage, the load curve steeply declines. The impactor then moves downward as the fracture propagates along and perpendicular to the fiber, and associated load graph shows a lengthy plateau after the peak load. At this point, there is noticeable depression on upper sheet and significant damage in impact area. Additionally, if the upper sheet sustains significant damage, honeycomb buckles and crushes to give a consistent resistance load. The energy curve shows similar pattern to the first case, except there is less energy for the rebound as the absorbed/dissipated energy of the test sample is almost same as the initial impact energy.

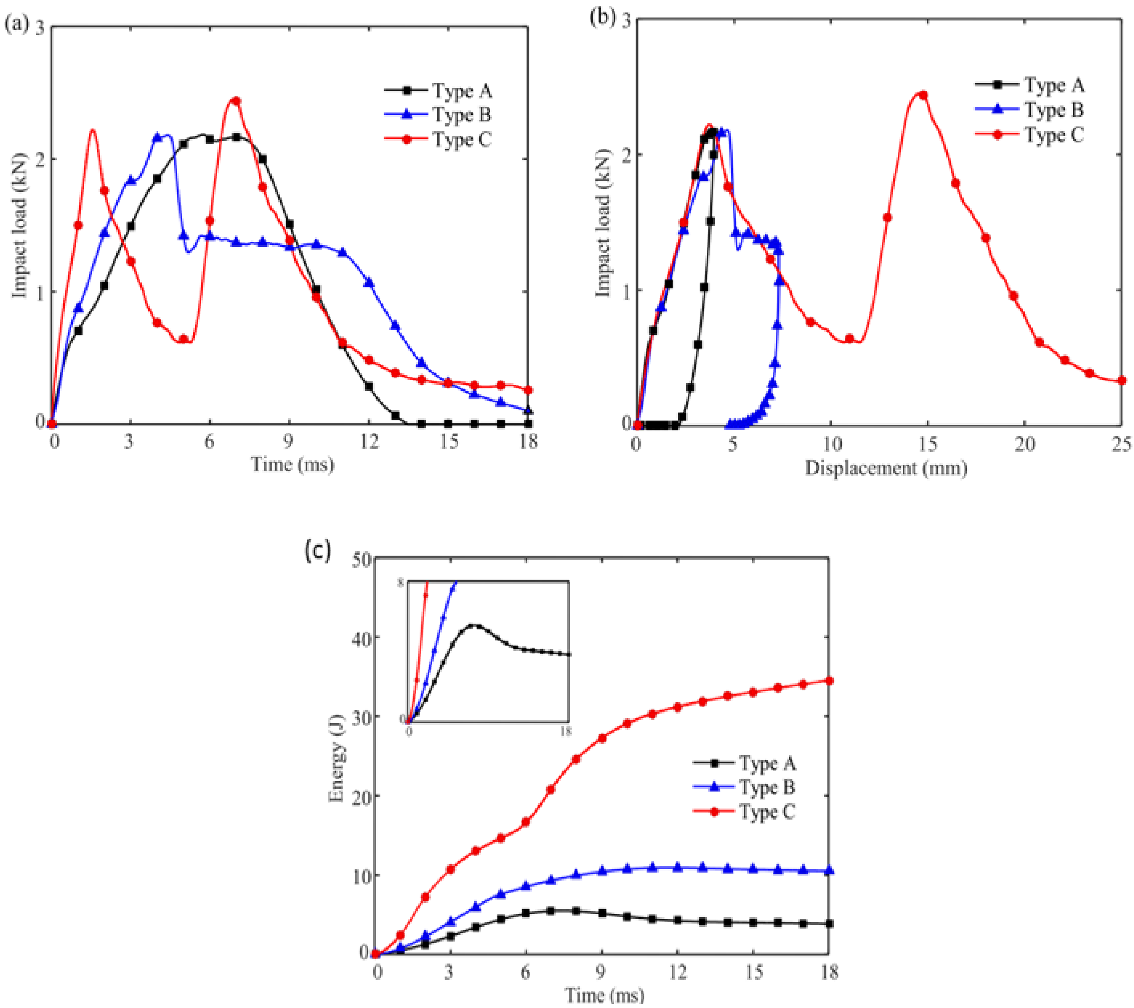

Figure 4.1: Typical Impact Behavior of Sandwich Panels

Type C is marked with two peak loads, signifying that the indenter makes sequential contact and penetrates the upper and lower face sheets. The force progressively decreases from a peak to a valley stage during the crack propagation stage following fracture initiation, which causes the top face sheet to completely penetrate and the core to crush beneath the impactor. The impactor then descends due to frictional force, interacting with the core and the failing upper face sheet. The cell walls of the honeycomb core experience gradual folding and crushing, which contributes to impact resistance. The load curve reflects this process, rising and then falling again when the impactor contacts the bottom face sheet, exhibiting a failure mechanism similar to the first peak. The corresponding energy curve shows two distinct rises, each stage corresponding to the interaction with the face sheets.

4.2 Experimental Results

Force vs. time and force vs. deformation graphs are used to assess and analyze the impact resistance of all three samples of the sandwich structure. A summary of these results is mentioned in **Table 4.1**. In order to identify the underlying damage and failure processes, a thorough research of the failure mechanisms and damage modes in all impacted specimens was carried out. The next sections provide a detailed discussion of these results.

Table 4.1: Experimental Testing Results of Sandwich Panel

Impact Energy (J)	Sample Type	Peak Load (kN) (SD)	Displacement @ Peak Load (mm)	Maximum Displacement (mm)	Absorbed Energy (J)
30	Conventional HC	2.7 (± 0.07)	9.15	16.30	28.6 (± 0.18)
	Hybrid HC – Foam Impact	3.54 (± 0.09)	9.46	13.82	29.4 (± 0.15)
	Hybrid HC – Grid Impact	3.09 (± 0.095)	7.1	12.5	25.2 (± 0.11)
45	Conventional HC	2.91 (± 0.1)	9.33	34.43	44.7 (± 0.53)
	Hybrid HC – Foam Impact	3.67 (± 0.087)	10.56	27.95	44.5 (± 0.21)
	Hybrid HC – Grid Impact	3.36 (± 0.12)	11.6	18.74	40.8 (± 0.37)

4.2.1 Force-Displacement Response

The force-displacement curve was created using the experimental data recorded during the impact test. A force sensor records data over time by continually measuring the impact force as it occurs. The BESMAK drop test tower program then carried out a series of numerical integrations to extract the deformation from the force vs. time data. The trapezoidal rule, and the Simpson's rule are examples of typical numerical integration algorithms [44]. Other sophisticated methods for precisely modelling the dynamic behavior of materials upon impact can also provide the force–deformation curves. The differential equations are solved using the Finite Difference Method (FDM) to approximate force–displacement connections [45]. Another method, the Bezier Multi-step Method [46], improves modelling accuracy by utilizing multi-step algorithms and Bezier curves to simulate force-deformation reactions.

The force-displacement curves provide valuable insight regarding peak force, peak displacement, bending stiffness and damage process. There are three key phases of the process during impact [47]: contact, deformation, and rebound or perforation. The first stage i.e. the contact phase is the elastic response phase. In this phase, the specimen exhibits only minimal elastic deformation with a small deflection. The load vs. time and load vs. displacement curves both show a linear rise, as the kinetic energy of indenter is converted into the specimen's elastic energy when the specimen drops from a height. Damage initiation and expansion constituted the second stage. When the impact load exceeded the initial damage threshold, indicated by first abrupt load drop, delamination started in specimen. The indenter then continued to descend to its lowest point. During this process, the contact force increased due to energy exchange, eventually reaching a maximum force that caused further delamination, matrix cracking, and fiber fracture. Some of the energy was absorbed and dispersed by the material, while the remaining energy was retained as elastic energy, contributing to the rebound of the impactor. If the structure cannot withstand the impact energy, the impactor will penetrate the structure, which is represented by a continuously increasing displacement on the curve.

The force vs. displacement curve for conventional honeycomb panel impact is shown in **Figure 4.2**. It can be observed that the deformation at peak force at 30J and 45J is 9.15 mm and 9.33 mm respectively while the maximum deformation at 30J and 45J is 16.3 mm and 34.43 mm respectively.

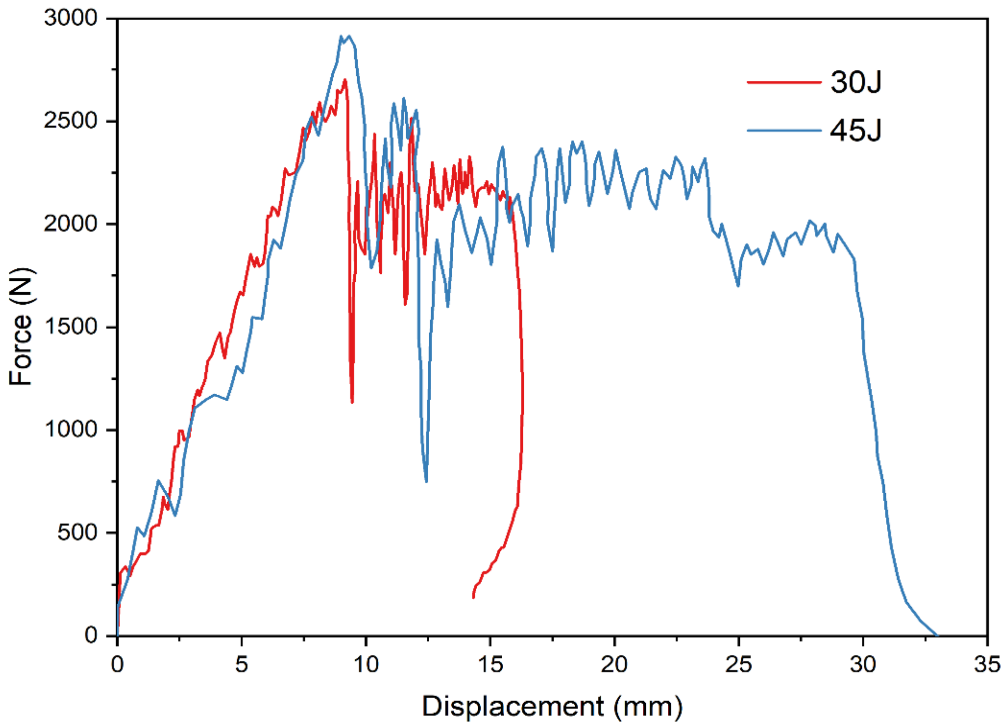

Figure 4.2: Force-Displacement Response for Conventional Honeycomb Impact

The force displacement curve for HHC sandwich panel with impact at foam location is shown in **Figure 4.3**. The deformation at peak force at 30J and 45J is 9.46 mm and 10.56 mm respectively while the maximum deformation at 30J and 45J is 13.82 mm and 27.95 mm respectively. The force displacement curve for HHC sandwich panel with impact at grid location is shown in **Figure 4.4**. The deformation at peak force at 30J and 45J is 7.1 mm and 11.6 mm respectively, while the maximum deformation at 30J and 45J is 12.5 mm and 18.74 mm respectively.

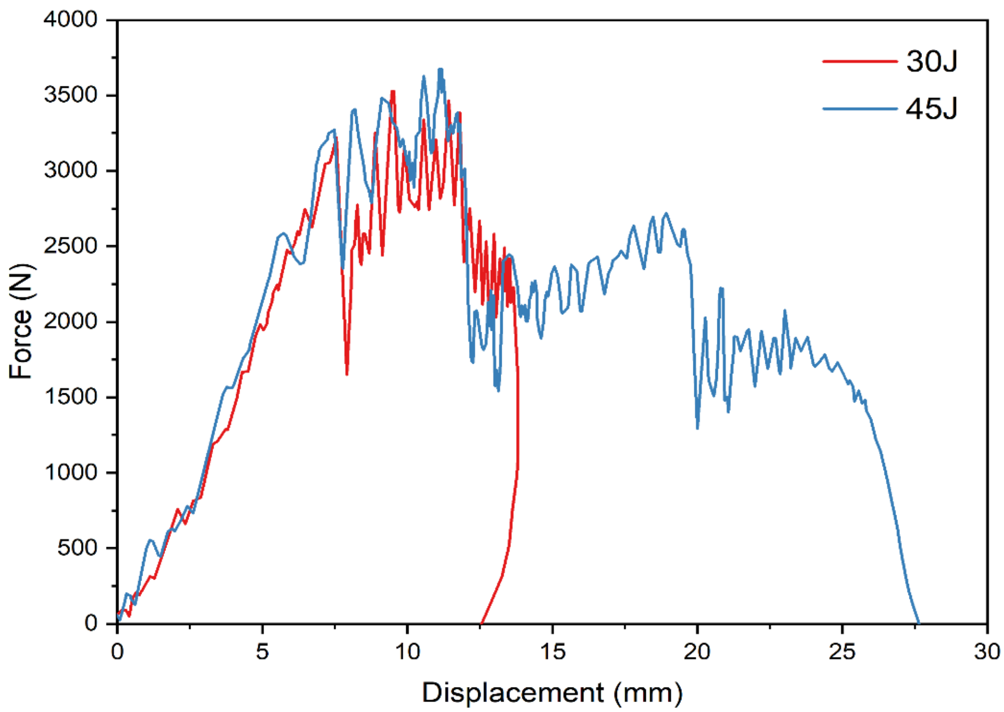

Figure 4.3: Force-Displacement Response for HHC Foam Impact

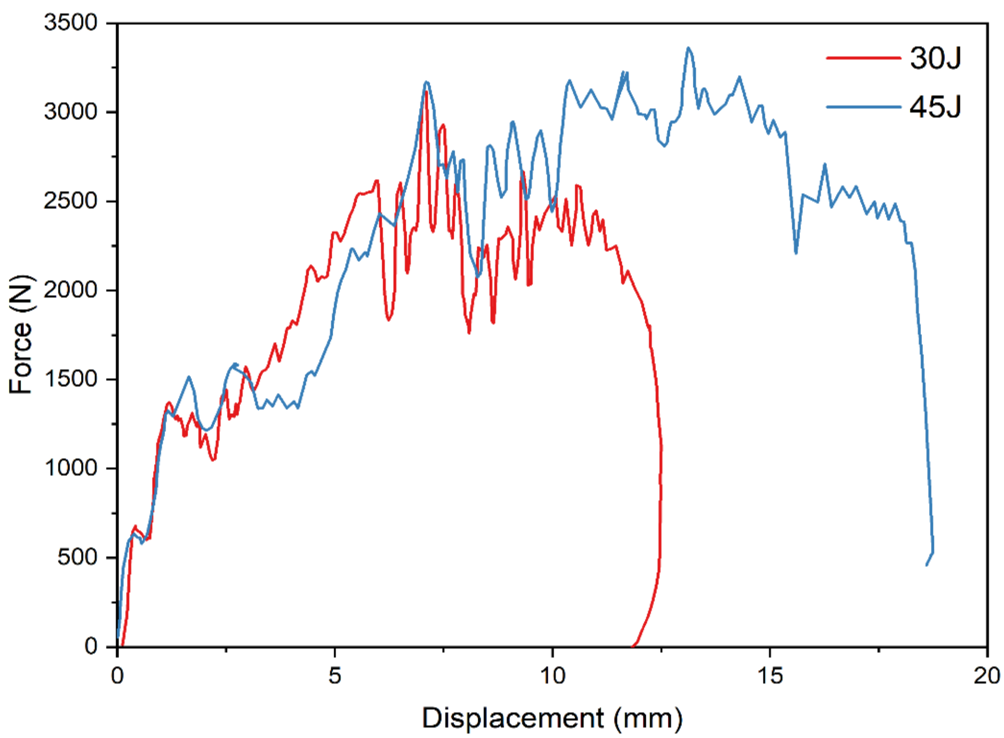

Figure 4.4: Force-Displacement Response for HHC Grid Impact

For a better insight regarding the maximum displacement occurring in each type of sample, the maximum displacements are compared with each other in **Figure 4.5**, based on the impact energy levels. The maximum displacement in both cases occurs in Conventional honeycomb sample while the minimum displacement in both cases occurs in HHC with impact at grid impact, showcasing the stiffness increase due to addition of grid. The chart also highlights that as energy increases, the maximum displacement also increases, but the increase in the maximum displacement is not linear, highlighting the complex damage phenomenon.

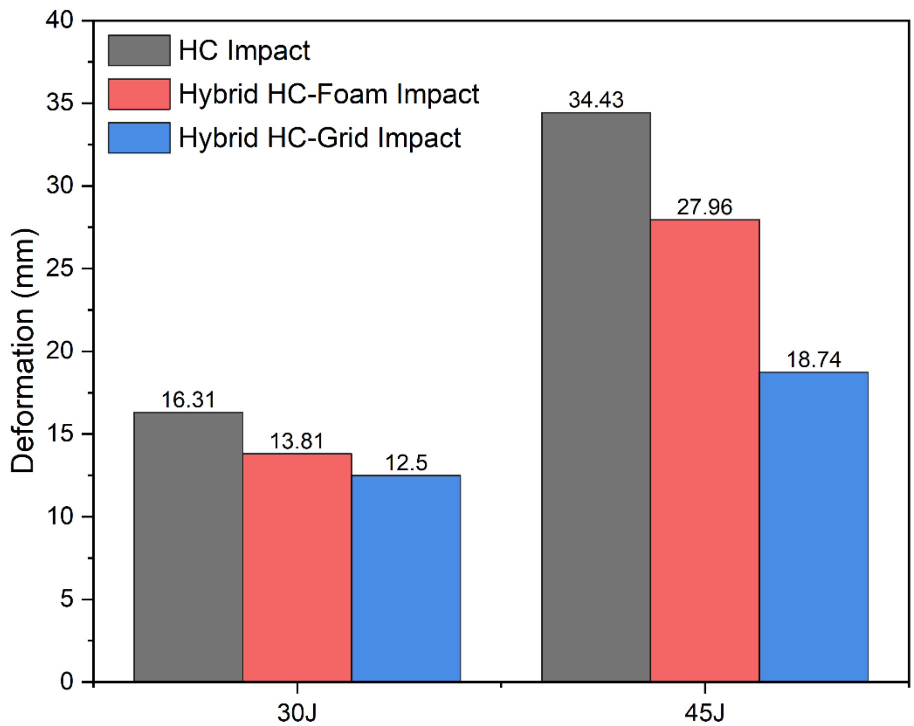

Figure 4.5: Maximum Displacement Comparison for all Samples

The force vs. displacement curves of all the samples at 30J and 45J are compared in **Figure 4.6** and **Figure 4.7** respectively. For all samples, the force-displacement curve at 30J exhibited a closed curve, representing that the impactor rebounded and no perforation occurred. On the contrary, the force-displacement curve at 45J that only HHC with grid impact showed close curve, implying no perforation. The curve for Conventional honeycomb impact and HHC with foam impact both displayed open curved suggesting perforation, with Conventional honey comb sample experiencing more perforation as compared to HHC core sample. The slope of the force vs. displacement curves illustrates the material's dynamic modulus. The change in the gradient of force-displacement curve throughout an impact test serves as an indicator of the damage transition and propagation of material [48]. HHC with grid impact showed the highest bending stiffness during the early stages, due to the added stiffness of aluminum grid. However, HHC with foam sustained the highest load, highlighting the energy absorption capabilities of foam and honeycomb. The first load drop indicates the damage initiation in the samples. All samples have comparable ascending sections at different energy levels but the descending sections demonstrate different behaviors because of different damage mechanisms.

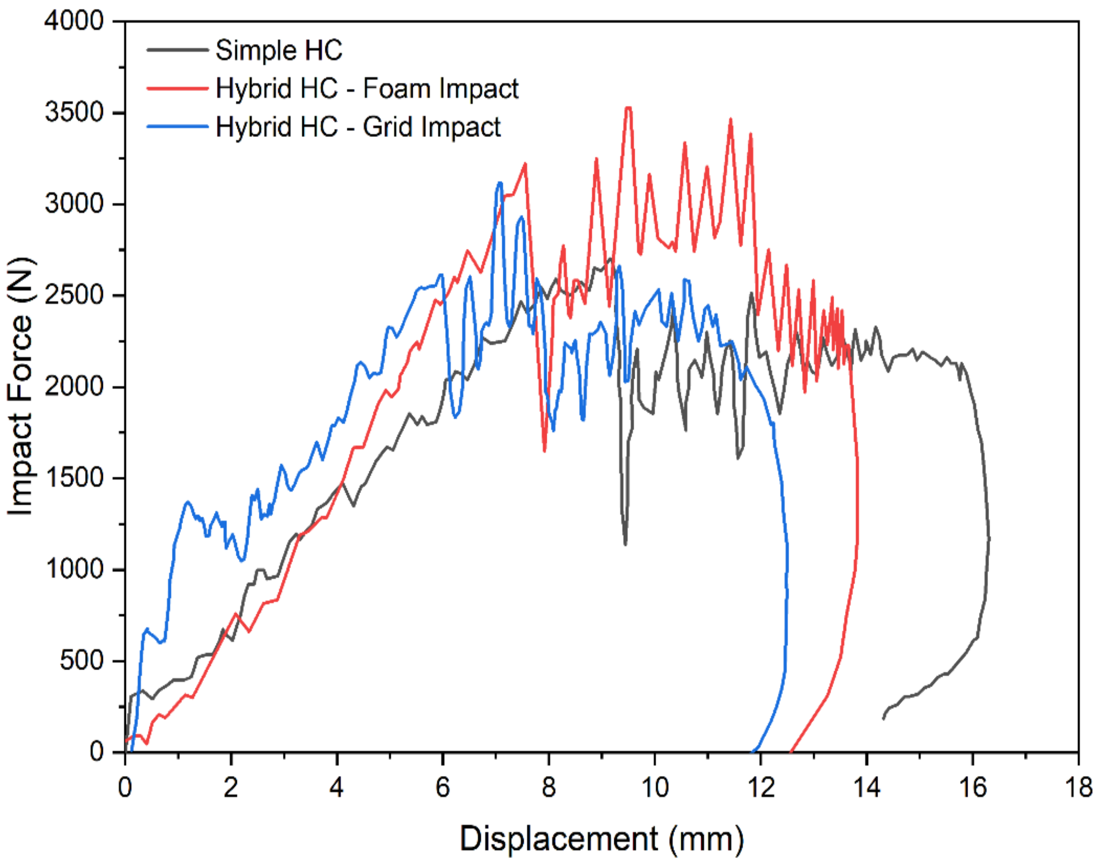

Figure 4.6: Force-Displacement Response for all Samples at 30J

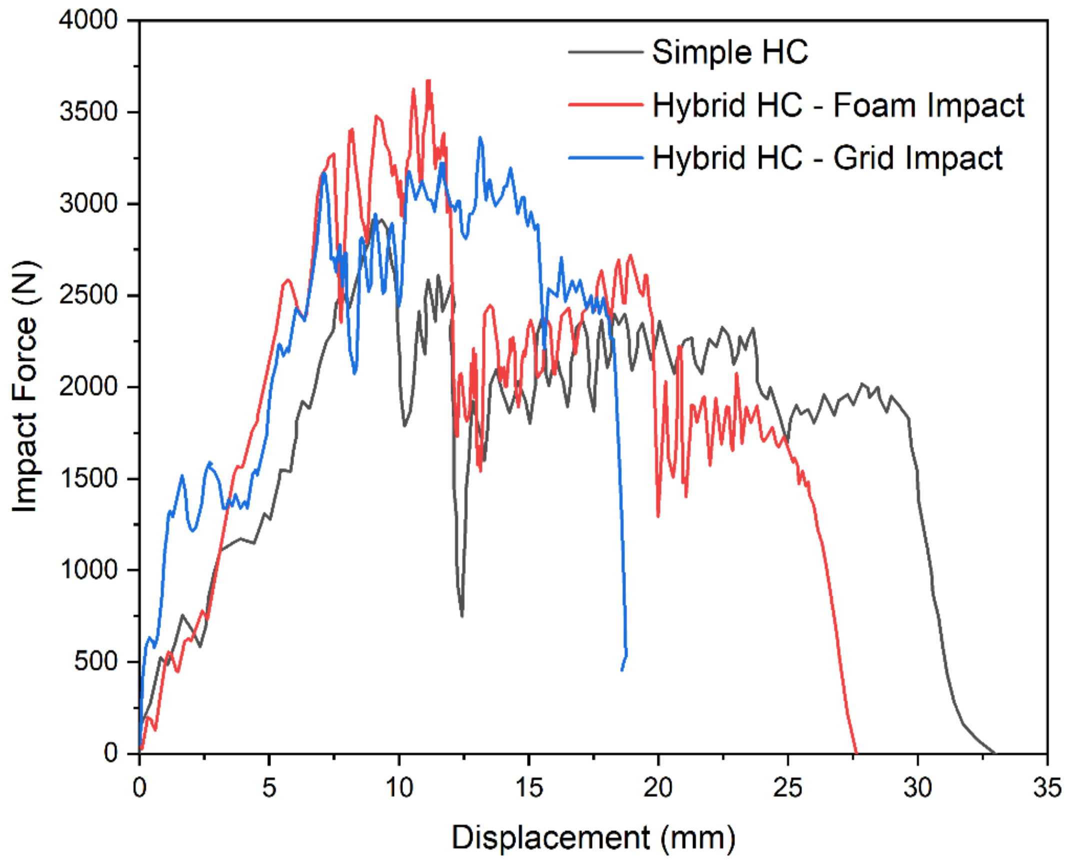

Figure 4.7: Force-Displacement Response for all Samples at 45J

4.2.2 Force-Time Response

The impact process is mainly categorized into three steps for the sandwich plates. The impact force first rises linearly and swiftly due to honeycomb's and facesheet's elastic modulus. After that, a steady but fluctuant state is reached by the contact force. In the experiment, the honeycomb core's buckling feature is primarily responsible for a stable phase. The fluctuating contact force is mostly caused by damage to the top facesheet. Finally, when impactor rebounds, the contact force progressively diminishes. The force-time curve for Conventional honeycomb sandwich panel impact is shown in **Figure 4.8**. The peak force at 30J and 45J is 2.7 kN and 2.91 kN respectively. The force-time curve for HHC sandwich panel with foam impact is shown in **Figure 4.9**. The peak force at 30J and 45J is 3.54 kN and 3.67 kN respectively. The force-time curve for HHC sandwich panel with grid impact is shown in **Figure 4.10**. The peak force at 30J and 45J is 3.09 kN and 3.36 kN respectively.

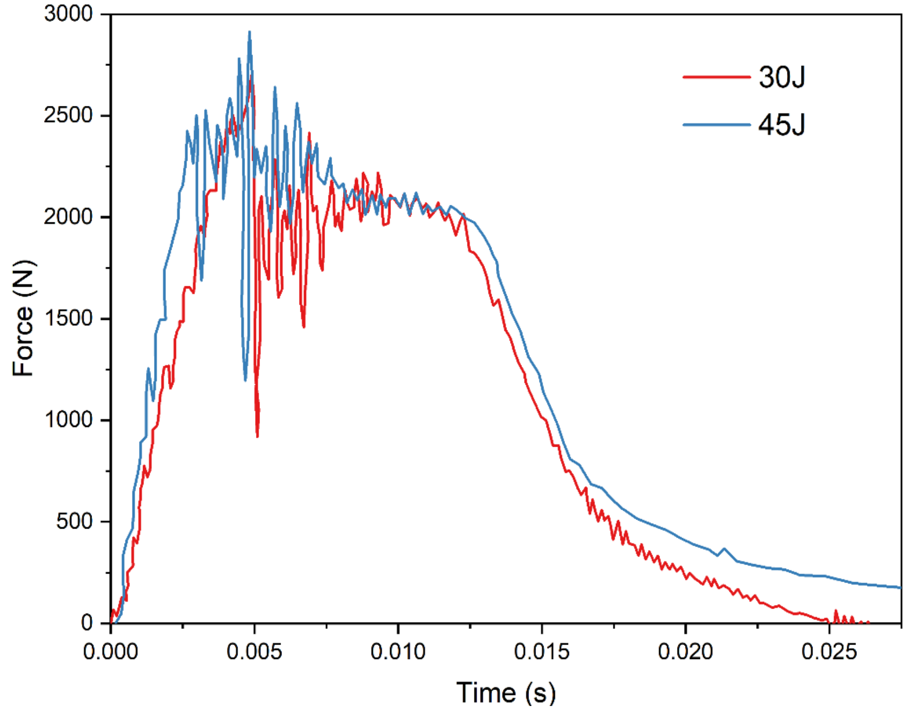

Figure 4.8: Force-Time Response for Conventional Honeycomb Impact

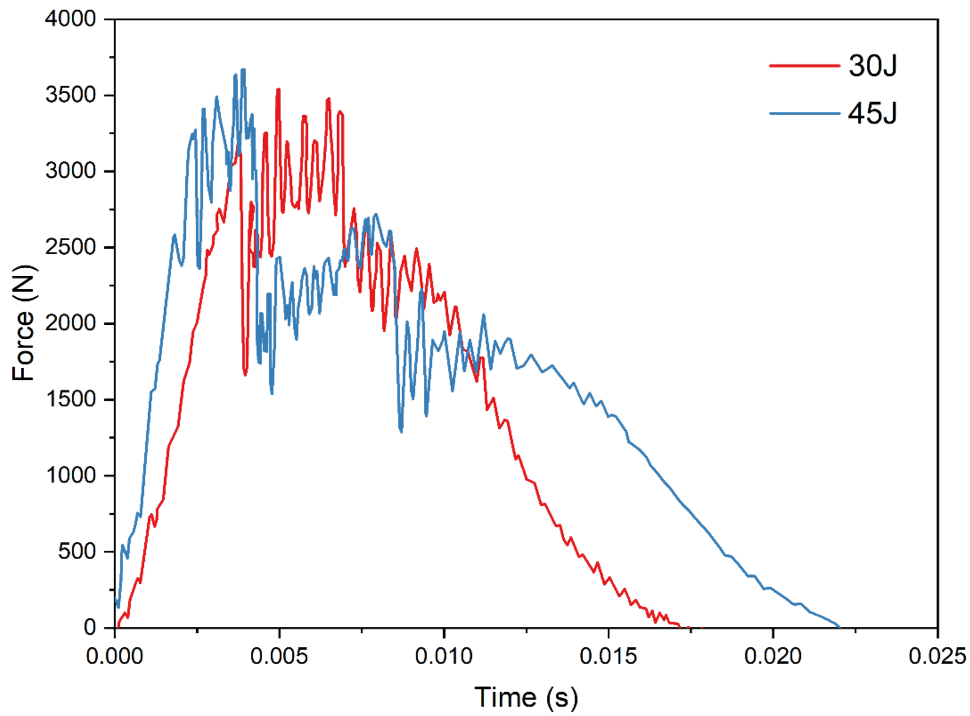

Figure 4.9: Force-Time Response for HHC Foam Impact

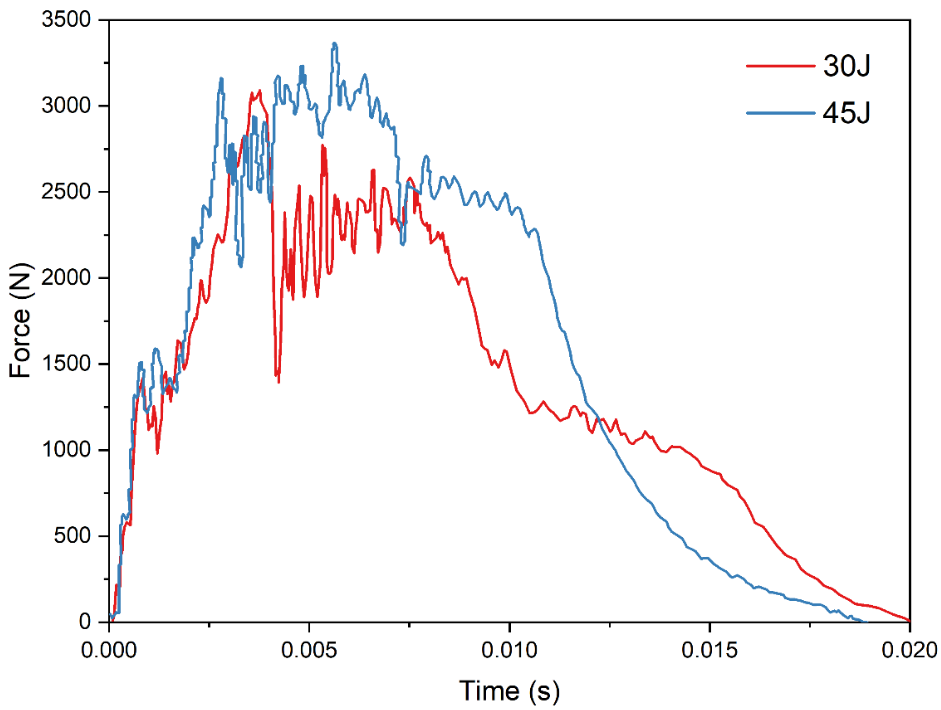

Figure 4.10: Force-Time Response for HHC Grid Impact

To obtain an in depth understanding of the peak impact force occurring in each type of sample, the peak impact force of each case is compared with each other in **Figure 4.11**, based on the impact-energy levels. The minimum peak force in both cases occurs in Conventional honeycomb sample while the maximum peak force in both cases occurs in HHC with impact at foam, followed by the HHC with impact at grid. The peak impact force in Conventional honeycomb is minimum in both cases, which shows that the Conventional honeycomb is the weakest panel as compared to HHC. The addition of grid and foam enhances the energy absorption ability of Conventional honeycomb and improves the impact resistance of sandwich panel.

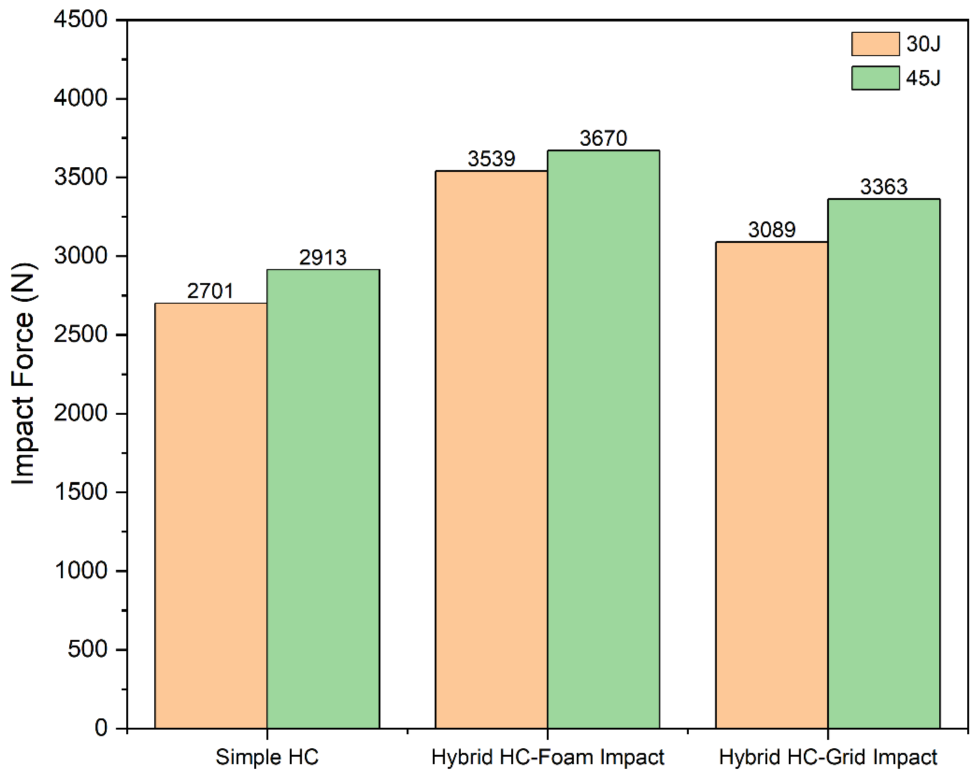

Figure 4.11: Peak Force Comparison for all Samples

The force vs. time curves of all the samples at 30J and 45J are compared with each other. It can be observed from **Figures 4.12** and **Figure 4.13** that the maximum force and total time increased as the impact energy increased. Another important aspect, which is apparent in the results is that the time to reach peak force decreased as the impact energy increased. This corresponds well with the trends of force-time curves found in literature [49]. There are two important thresholds in the load history of low velocity impact testing. The first threshold, occurring at first load decrease is associated with the initial material damage. The sharp rise and substantial oscillations at the initial phase indicate the inception of material damage, mainly damage in facesheet. The second threshold is associated with the specimen's damage at maximum impact force. Further, the impact force-time graph for Conventional honeycomb impact and foam impact show rapid decline after reaching the peak load, which characterized the facesheet damage and penetration occurring in these samples. The slope of impact force-time curve doesn't remain constant, with the initial stiffer portion of the curve corresponding to the non-damaged state followed by the reduction of slope due to internal damage. The initial stiffness for grid impact was higher as compared to that of honeycomb and foam impact for both energy levels. It's because the grid generated a high degree of local stiffness by supporting the structure vertically, which limited the amount of elastic-plastic deformation of the sandwich panel. Furthermore, when the impact location was the honeycomb and foam, the sandwich panel produced a stable plastic crush deformation due to the thin walled shell structure of the honeycomb and cellular structure of foam. This resulted in a load plateau after the peak in the impact-force curve. Moreover, by inspecting the curves, it is apparent that the HHC core sandwich panel shows much superior performance as compared to Conventional honeycomb core sandwich panel at both energy levels.

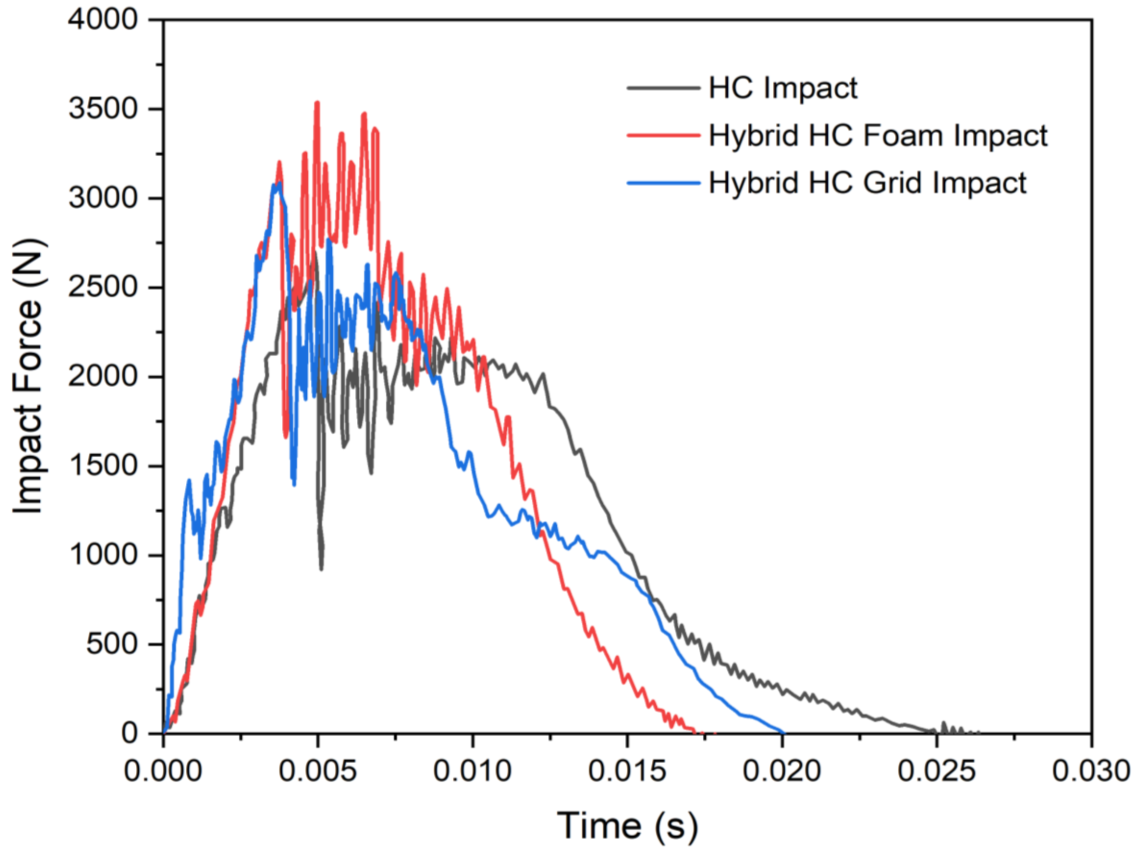

Figure 4.12: Force-Time Response of all Samples at 30J

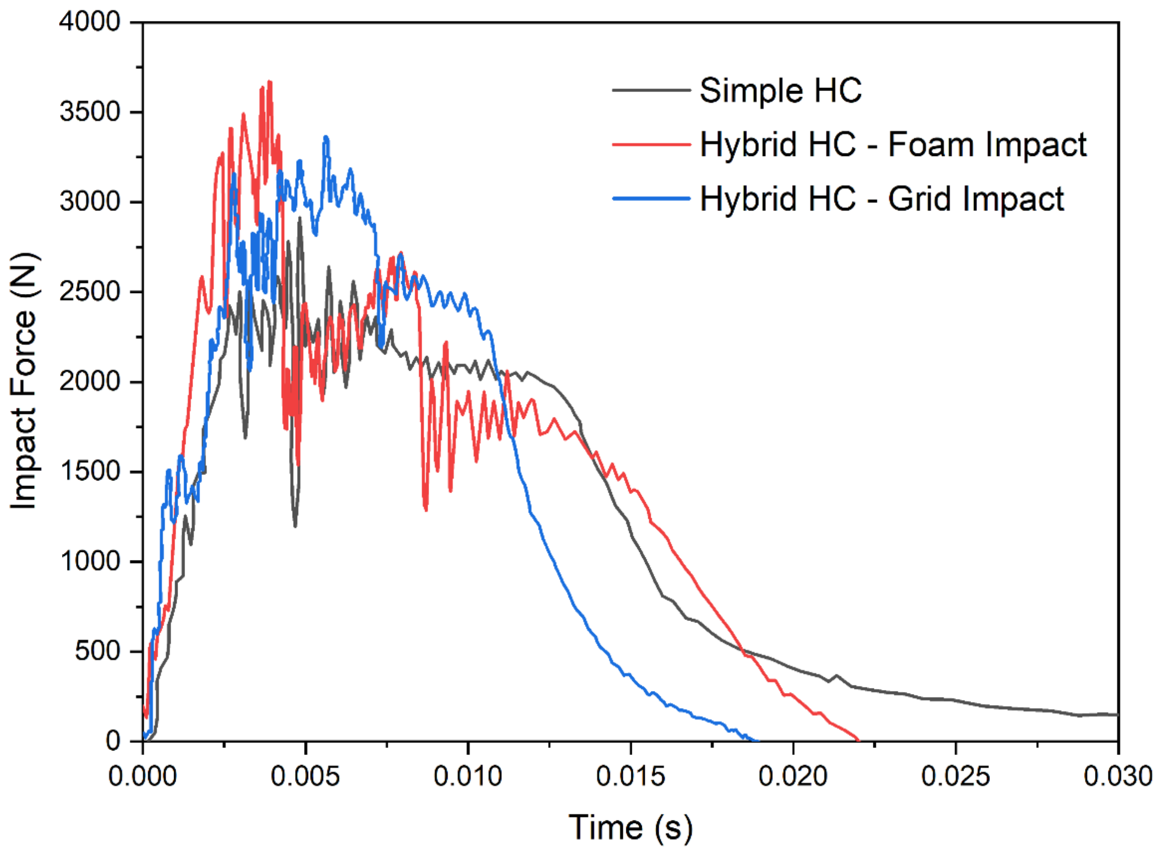

Figure 4.13: Force-Time Response of all Samples at 30J

4.2.3 Energy-Time Graphs

The absorbed energy by the specimen vs time graphs were obtained using the equation 5.1. A typical energy-time graph is shown in **Figure 4.14**.

$$E_{abs}(t) = \frac{m({v_i}^2 - \mathrm{v(t)}^2)}{2} + mg\delta(t) \qquad (5.1)$$

Where:

E_{abs} = Absorbed Energy, J

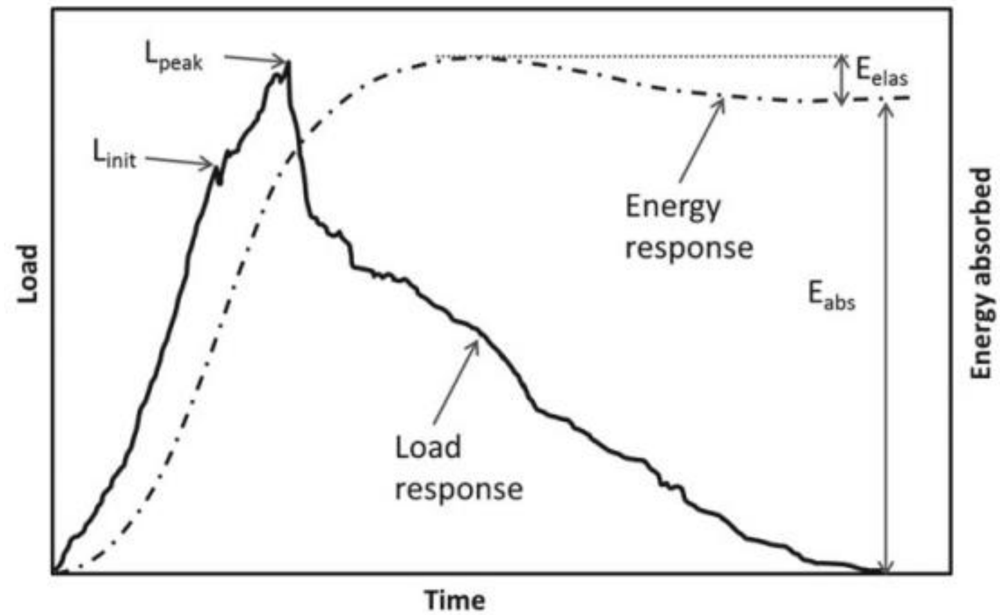

Figure 4.14: Typical Energy Response of a Structure under Impact Loading

In a few test samples, the absorbed/dissipated energy are less than the corresponding impact energies. The impactor uses the drop-weight system's surplus impact energy, which is stored there, to rebound off the test specimen. It can be observed that the Conventional honeycomb core sandwich panel and HHC core sandwich panel with foam impact exhibited similar behavior for both energy levels. This is due to the fact that both foam and honeycomb behave in a similar fashion when subjected to impact loads. The curves also show that the absorbed energy in Conventional honeycomb core sandwich panel and HHC core sandwich panel with foam impact is highest while the absorbed energy in HHC core sandwich panel with grid impact is smaller. This indicates that impact at grid resulted in minimum internal damage and the impact at honeycomb and foam location caused maximum internal damage such as delamination, fiber damage and core crush.

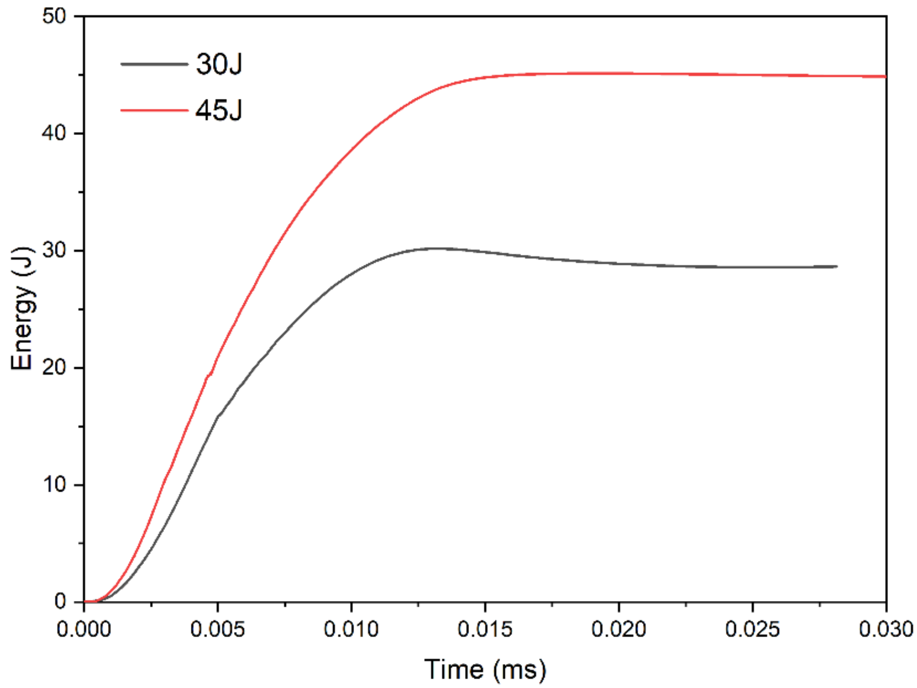

Figure 4.15: Absorbed Energy - Conventional Honeycomb

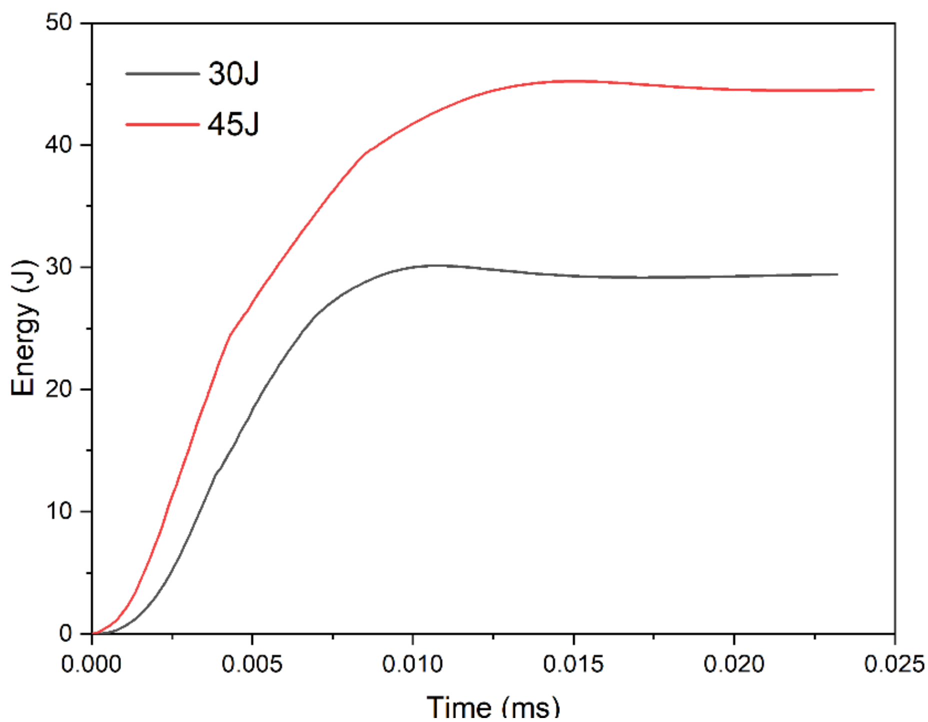

Figure 4.16: Absorbed Energy - HHC-Foam Impact

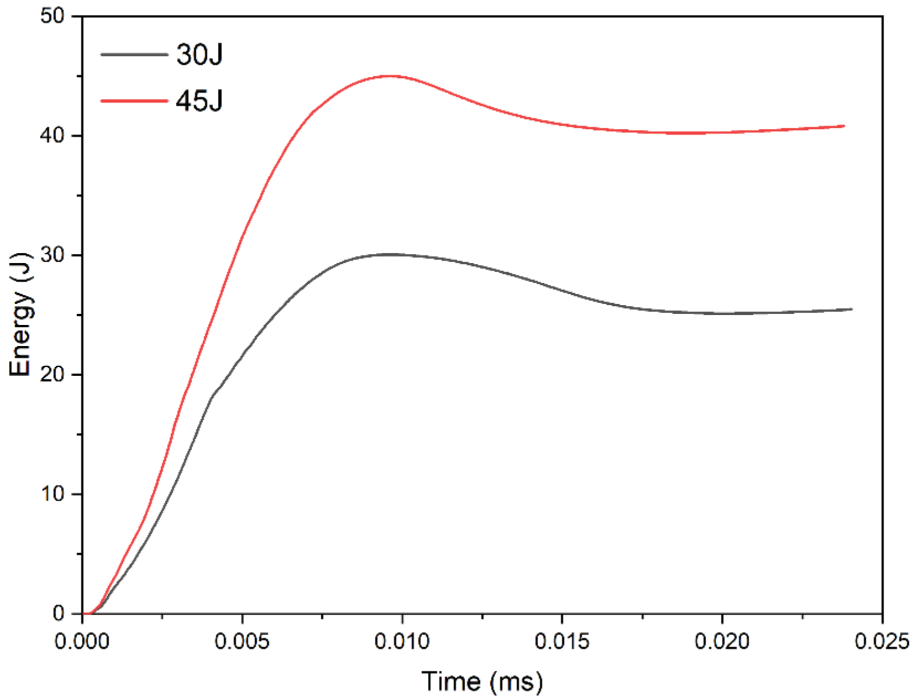

Figure 4.17: Absorbed Energy - HHC-Grid Impact

4.2.4 Velocity-Time Graphs

Impactor velocity-time graphs were obtained using the equation 5.2 and numerical integration of force- time data. The typical numerical integration algorithms include the Simpson's rule and Trapezoidal rule. A positive velocity value represents downward movement while a negative velocity value represents upward movement (rebound). It is critical to examine the velocity-time graph in low velocity drop weight impact testing to understand how structure react to impact loads. It offers understanding of how damage, such as fiber breaking, delamination and matrix cracking, begins and progresses within the materials. Velocity-time graphs of composites sandwich panels are shown below.

$$v(t) = v_i + gt - \int_0^t \frac{F(t)}{m} dt \quad (5.2)$$

Where:

v = velocity of impactor at time t, m/s

v_i = velocity of impactor at initial contact t_i, m/s

t = test time,

F = contact force at time t, N

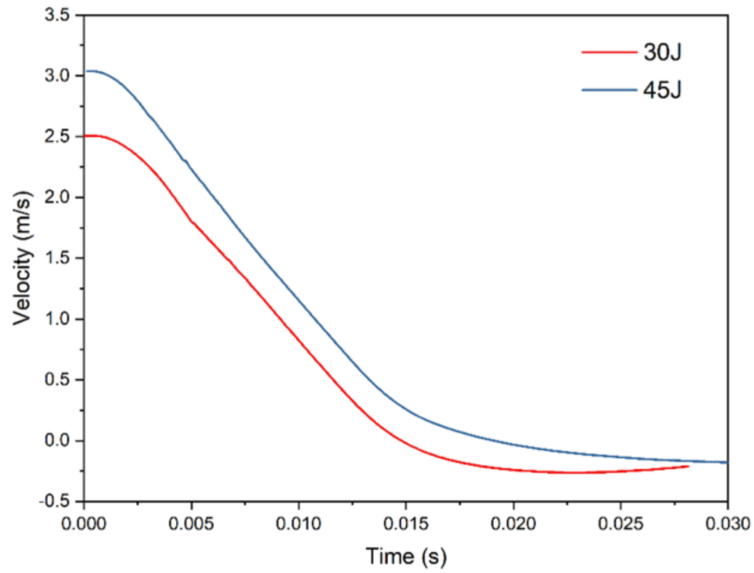

Figure 4.18: Velocity-Time Response of Conventional HC

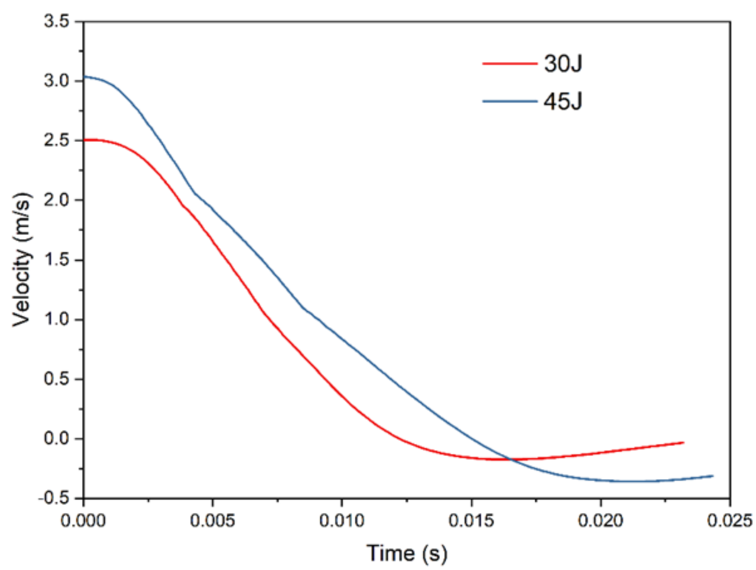

Figure 4.19: Velocity-Time Response of HHC-Foam Impact

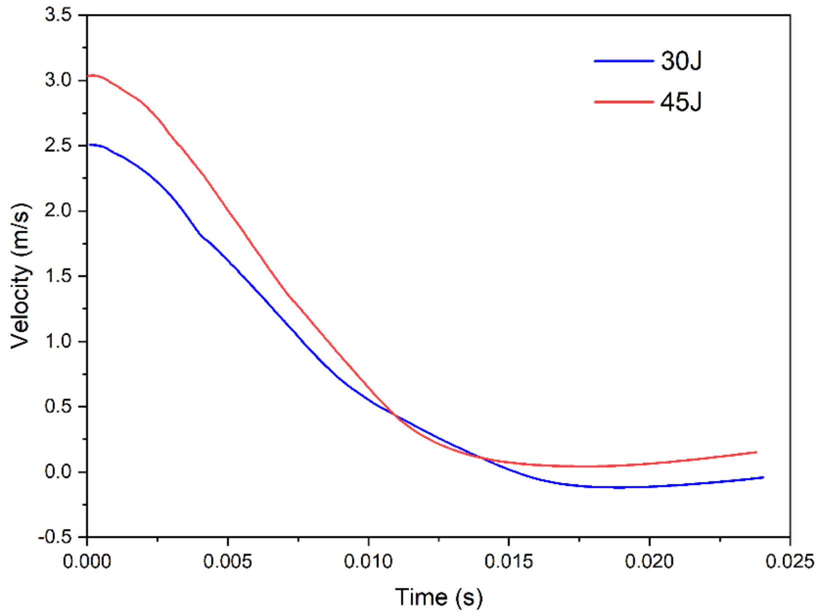

Figure 4.20: Velocity-Time Response of HHC-Grid Impact

4.2.5 Displacement-Time Graphs

Displacement-time graphs are calculated using the equation

$$\delta(t) = \delta_i + v_i t + \frac{gt^2}{2} - \int_0^t \left(\int_0^t \frac{F(t)}{m} dt \right) dt \qquad (5.3)$$

Where:

δ = displacement of impactor at time t

δ_i = displacement of impactor from reference location at time t=0

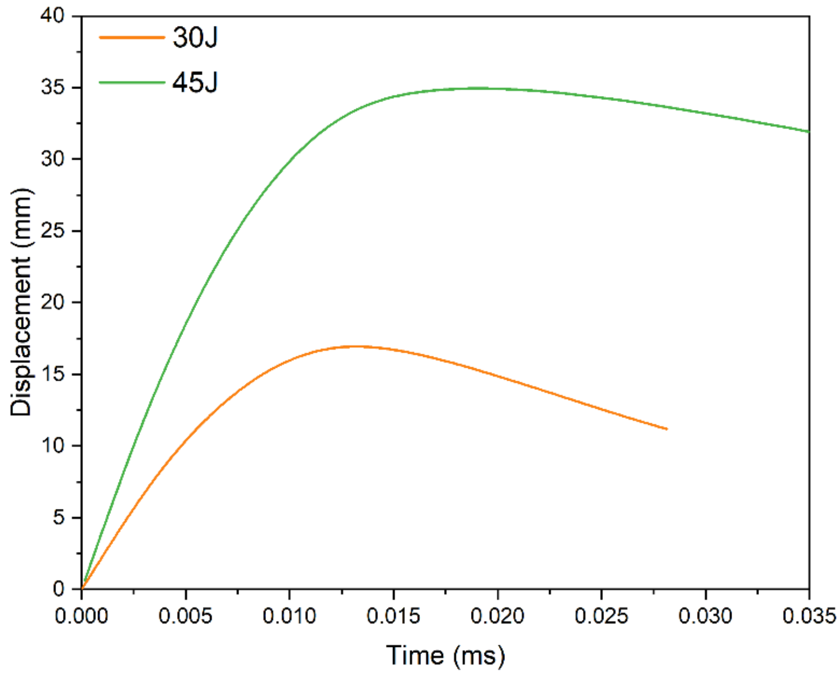

Figure 4.21: Displacement-Time Response of Conventional HC

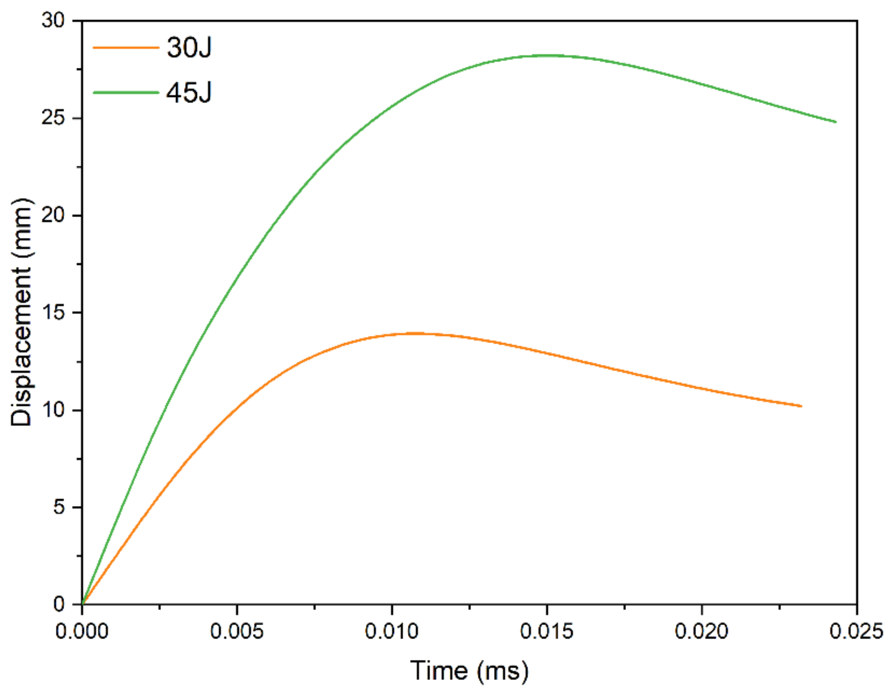

Figure 4.22: Displacement-Time Response of HHC-Foam Impact

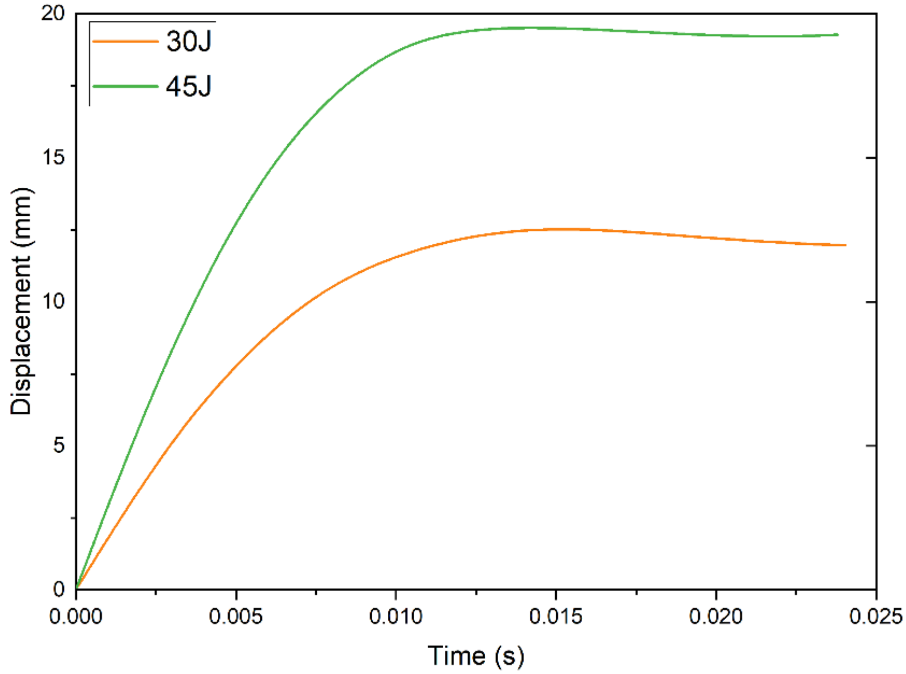

Figure 4.23: Displacement-Time Response of HHC-Gird Impact

4.2.6 Indentation Measurement

Following the impact testing, an analysis was conducted to determine the indentation caused by the impactor under impact load in each of the three distinct specimens. The specimen's permanent indentation created by the indenter was measured using a dial gauge. As the impactor comes in contact with the specimen, the specimen develops a dent on its surface due to the energy transfer upon contact. The size of the indentation increases in all three configurations as the energy input increases, although not proportionally in each instance as shown in **Figure 4.24.** Conventional honeycomb impact & HHC foam impact show greater indentations at both energy levels, while HHC with grid impact shows minimum indentation at both energy levels. The maximum indentation occurs in Conventional honeycomb impact at 45J, highlighting the perforation of sample. This differential response highlights the complex relationship between impact energy and the resultant damage characteristics, underscoring the importance of configuration in controlling the subsequent indentation damage under changing energy circumstances.

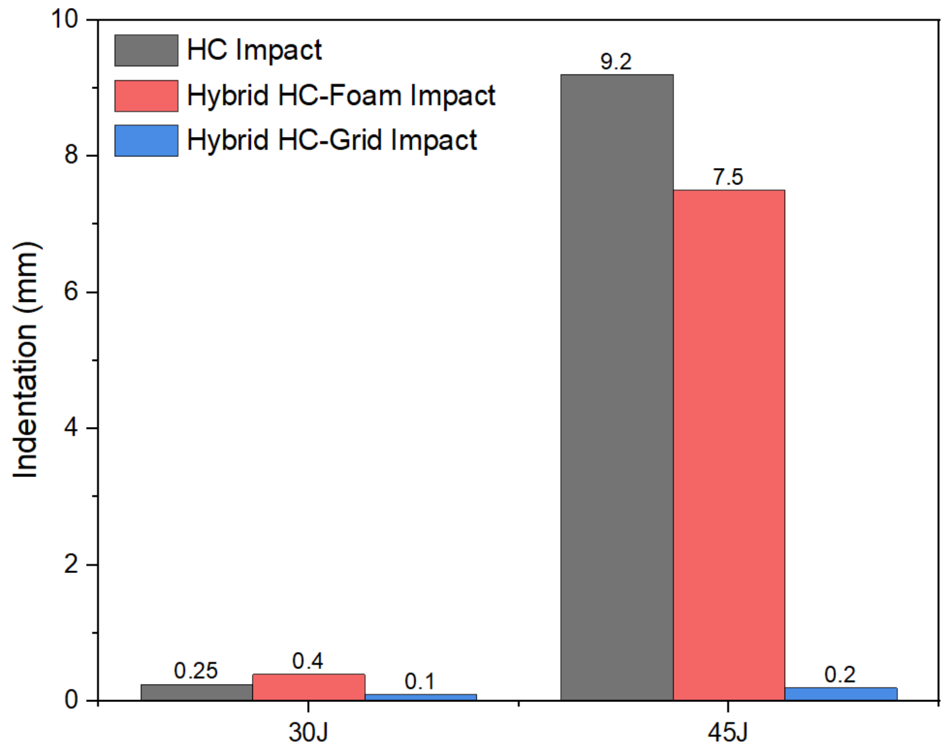

Figure 4.24: Comparison of Indentation of Conventional HC, HHC-Foam and HHC-Grid at 30J and 45J

4.2.7 Damage Characterization of Low Velocity Impact

The damaged area as a result of impact was measured by digital image processing for all samples. The damaged area along with damage types for the impact and non-impact faces of each configuration is shown in **Figure 4.25**. Permanent indentation, which results in various localized failure modes, is one of the primary methods for energy absorption in sandwich panels. The indentation immediately after an impact is always greater and requires some time to relax to reach its equilibrium state [50]. Therefore, the permanent indentations were recorded after a relaxation period of 48 h.

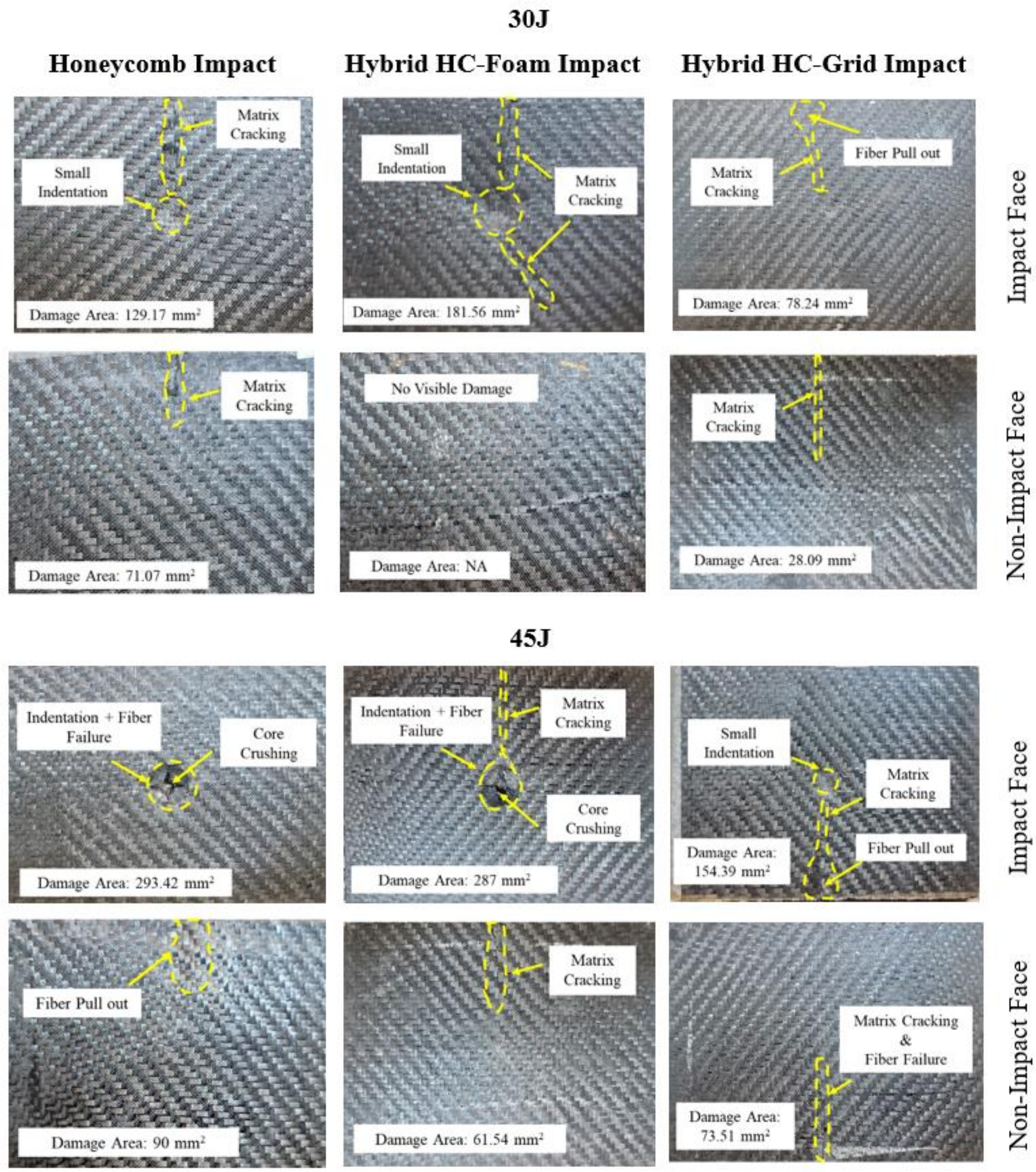

Figure 4.25: Analyzing Macroscopic Failure Modes of Impact and Non-Impact Sides of Sandwich Panels

At 30J, matrix cracking was observed for all samples on impact face. For conventional honeycomb impact and HHC foam impact, small indentations were clearly visible while HHC grid impact exhibited barely visible indentation. For non-impact face, matrix cracking was observed for conventional honeycomb impact and HHC grid impact. Although, the maximum damage area at impact face occurred in HHC foam impact, but the damage was only present on impact face, with no visible damage on non-impact face. This showed that the foam core sustained damage in a better way and did not transfer it to the bottom face sheet.

At 45J, all the samples showed indentation, with Conventional honeycomb and HHC with foam impact showing the maximum indentation. Matric cracking and fiber failure was also present at impact and non-impact face. The indentation in conventional honeycomb and HHC with foam impact also caused core crushing, with facesheet-core debonding occurring in Conventional honeycomb. This showed that the addition of grid and from to honeycomb to achieve the HHC improved the interface of facesheet and core, resulting in better damage transition. Similar to the impact at 30J, the HHC with foam impact showed less damage as compared to the conventional honeycomb on the non-impact face. Overall, HHC showed less damage on the non-impact face as compared to Conventional honeycomb for both grid and foam impact at both energy levels.

The damage area of impact face for all samples is compared with each other and shown in F**igure 4.26.** The damage area for grid impact is minimum for both energy levels. HHC with foam impact shows maximum damage are for impact at 30J while conventional honeycomb shows maximum damage area for 45J.

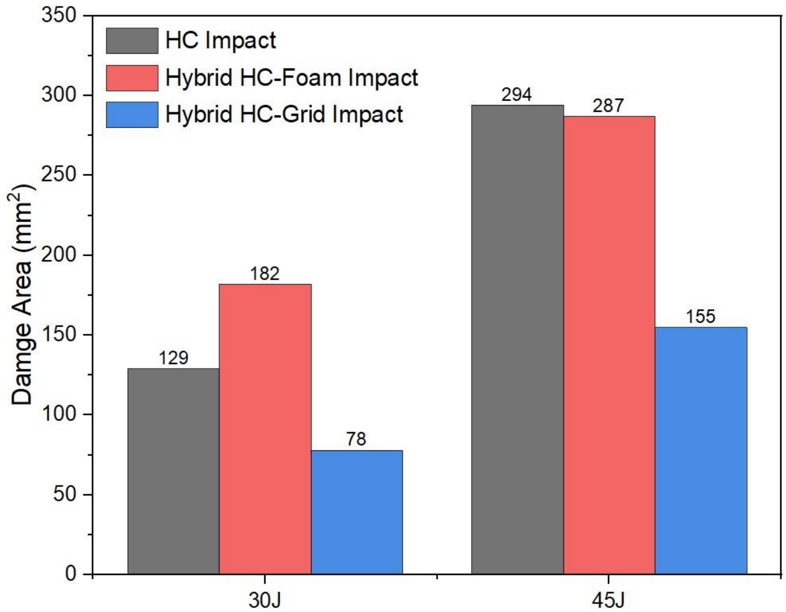

Figure 4.26: Comparison of Damage Area on Impact Face of Conventional HC, HHC-Foam & HHC-Grid at 30J and 45J

In order to understand the failure mechanism occurring in each specimen in more details, a cross section is cut at the impact site. The cross section of samples with different types of damages occurring is shown in detail in **Figure 4.27** and **Figure 4.28**. At 30J, delamination is the dominant mode in all of the samples. For conventional honeycomb impact, honeycomb undergoes buckling at the impact site, while core shearing is also evident. For HHC foam impact, some buckling is seen in honeycomb at the impact site along with core shearing but the damage is less as compared to conventional honeycomb, although the delamination is greater. For grid impact, very little core shearing is observed in core.

At 45J, major damage is seen in core for conventional honeycomb and HHC foam impact, although the depth of damage is greater in conventional honeycomb impact. Core crushing is seen in both these samples along with severe delamination and fiber failure at impact site, while core buckling is observed in regions closed by. One important difference to note is the facesheet-core debonding occurring in conventional honeycomb impact, which is not present in the HHC foam impact. This shows that the interfacial bonding between the core and facesheet improved due to addition of foam and grid in honeycomb.

For HHC with grid impact, major damage manifested itself in the form of core shearing, with delamination also present. The impact on grid also caused the bending of aluminum grid, which caused the face-sheet core debonding at this energy level.

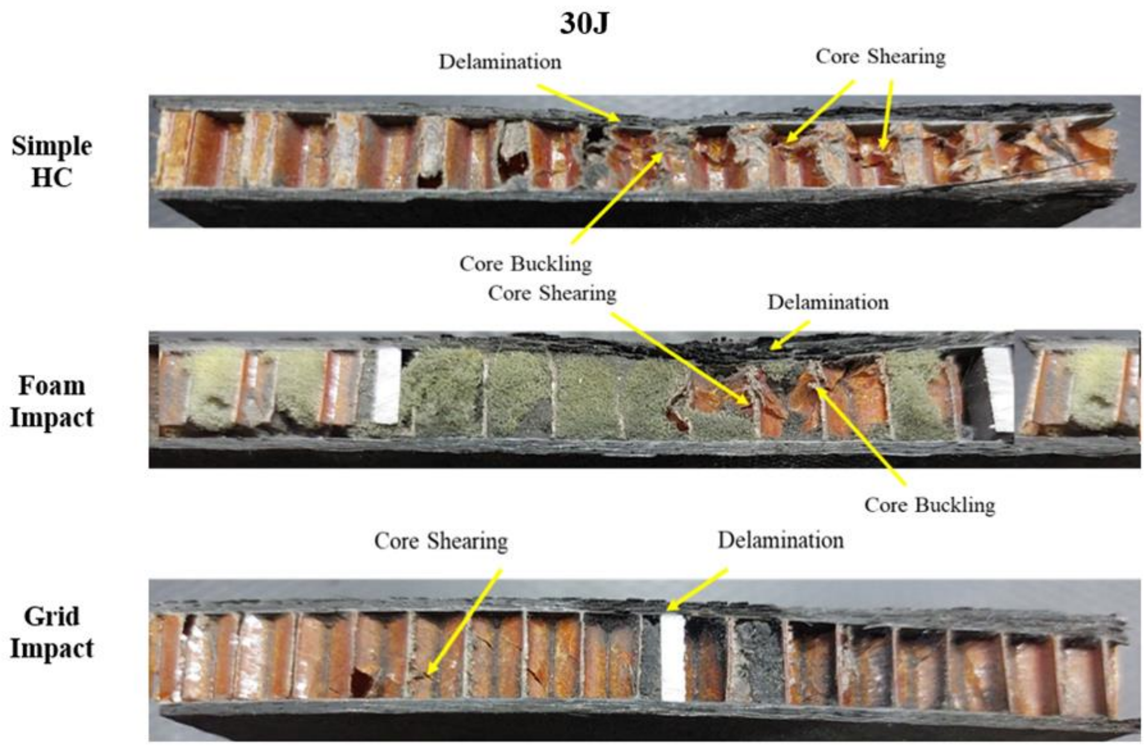

Figure 4.27: Internal Damage Characterization of All Samples at 30J

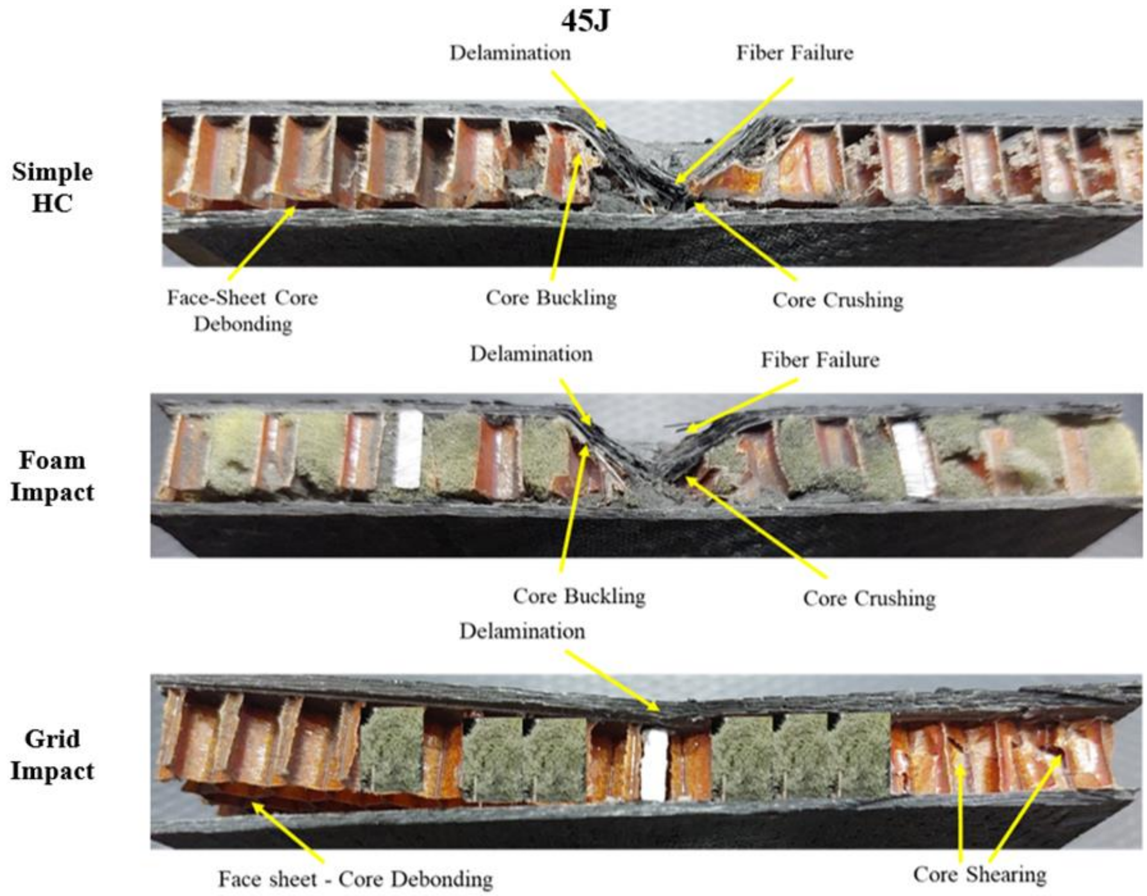

Figure 4.28: Internal Damage Characterization of All Samples at 45J

4.2.8 Performance Index (PI) of Sandwich Structures

In order to compare the impact performance of HHC with conventional honeycomb, a performance index is defined. The performance index is calculated as the ratio of peak force of HHC to the peak force of conventional honeycomb. A value of greater than one shows that the HHC is performing better than the conventional honeycomb. **Figure 4.29** shows that the HHC shows better performance as compared to Conventional honeycomb for both grid and foam impact. The PI is better for foam impact as compared to gird impact, showing that the addition of foam increased the peak load of sandwich structure. Overall, addition of foam and grid is beneficial for the impact resistance of sandwich pane.

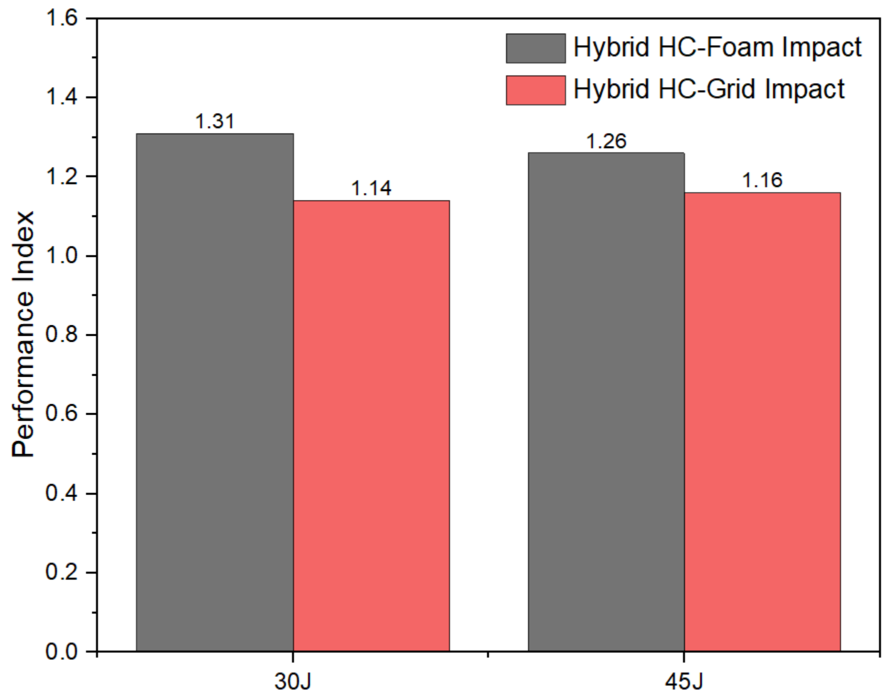

Figure 4.29: Performance Index of HHC Core Sandwich panels at 30J & 45J Impact

CHAPTER 5: CONCLUSION

The impact testing for conventional honeycomb core sandwich panel and HHC core sandwich panel were carried out at two energy levels. The impact response of sandwich panel was recorded in the form of force vs. time, force vs. displacement, velocity vs. time, energy vs. time and displacement vs. time curves. Other metrics like indentation and performance index of sandwich panel were also calculated. The conclusions from the research are:

- During the impact test, HHC foam impact sustained maximum peak force. The peak force for HHC foam impact was 1.31 and 1.26 times higher as compared to conventional honeycomb impact whereas the peak force for HHC grid impact was 1.14 and 1.16 times higher as compared to conventional honeycomb impact.
- The HHC core sandwich panel, due to addition of grid and foam, exhibited better bending stiffness as compared to conventional honeycomb core sandwich panels.
- For impact at 30J, all samples displayed a closed force displacement curve, showing that no perforation occurred at this level. For impact at 45J, conventional honeycomb impact and HHC foam impact demonstrated an open force-displacement curve, demonstrating the perforation in samples. However, the perforation in HHC was lower as compared to conventional honeycomb.
- Macroscopic analysis of failure mode shows that the matrix cracking is present in almost all samples. For 30J, indentations are present on the impact face of conventional honeycomb and HHC foam impact. Conventional honeycomb impact shows damage on both impact and non-impact face. HHC core panels exhibit better impact damage characteristics, with no visible damage on non-impact face of foam impact, while the grid impact shows minimum damage area overall. For 45J, perforation occurs for conventional honeycomb impact and HHC foam impact while small indentation is present for HHC grid impact.

Overall, the damage on non-impact face of HHC core panel is lower as compared to conventional honeycomb core panel.

- The cross-sectional damage analysis of samples sheds light on the critical damage modes occurring in sandwich panels as a result of impact. Delamination is the most dominant mode in all the samples, which is in accordance with literature. Delamination is most severe for conventional honeycomb sandwich panels for both energy levels. Core crushing and core buckling are also present at the impact site. Conventional honeycomb at 45J impact shows the maximum core crushing, with facesheet-core debonding also visible, whereas no debonding is observed in HHC foam impact. This is because of the improved interface between facesheet and core in HHC due to addition of foam and grid. Core shearing is dominant in HHC grid impact due to the stiffness of grid. The impact on grid causes the bending of grid, resulting in a partial debonding of face sheet and core.

Overall, the research highlights the advantages of adding grid and foam to honeycomb. The performance of HHC core sandwich panels was much improved as compared to conventional honeycomb sore sandwich panel. Peak force, displacement and indentation were all much better and the sandwich panel displayed superior impact resistance and damage characteristics. Therefore, sandwich panels with HHC core are beneficial and can be used as a replacement of conventional honeycomb core sandwich panels.

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