INVESTIGATION OF ENERGY ABSORPTION CAPACITY OF SANDWICH COMPOSITES SUBJECTED TO THE IMPACT LOADINGS

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by
Aidel Kadum Jassim AL-SHAMARY

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A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of Science
in Mechanical Engineering, Mechanics Program

by
Aidel Kadum Jassim AL-SHAMARY

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"INVESTIGATION OF ENERGY ABSORPTION CAPACITY OF SANDWICH COMPOSITES SUBJECTED TO THE IMPACT LOADINGS"** completed by **AIDEL KADUM JASSIM ALSHAMARY** under supervision of **PROF. DR. RAMAZAN KARAKUZU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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INVESTIGATION OF ENERGY ABSORPTION CAPACITY OF SANDWICH COMPOSITES SUBJECTED TO THE IMPACT LOADINGS

ABSTRACT

Sandwich composites are used in many diverse areas like complex aircraft and automobile parts, wind turbine blades and cage systems. This is due to appealing mechanical properties such as acoustic damping, high bending stiffness, and excellent thermal insulation etc.

In the present work, sandwich composite plates were manufactured by using vacuum assisted resin infusion molding (VARIM). E-glass fabrics zero per ninety having density of 300 gram per meter square as the reinforcing material and Epoxy ARALDITE LY 1564 SP resin and ARADUR 3487B hardener as the matrix material were used. Specimens prepared with dimensions 100 mm square were subjected to low velocity impact (LVI). Impactor height is various to give a level of impact energy from 10J to 50J with constant impactor mass of 5 kg.

Contact force–time, contact force–deflection, contact force–impact energy, deflection- impact energy, time-impact energy and absorbed energy-impact energy have been depicted by using 10J, 20J, 35J and 50J impact energy levels.

Keywords: Sandwich composite, E-Glass fiber, low velocity impact, PVC foam, two-core

DARBE YÜKLERİNE MARUZ SANDVİÇ KOMPOZİTLERİN ENERJİ ABSORBE ETME KAPASİTESİNİN ARAŞTIRILMASI

ÖZ

Sandviç Kompozit karmaşık uçak ve otomobil parçaları, rüzgâr türbin kanatları ve kafes sistemleri gibi birçok çeşitli alanlarda akustik sönümleme, yüksek eğilme sertliği ve mükemmel ısı yalıtımı gibi mekanik özellikleri nedeniyle kullanılmaktadır.

Bu çalışmada, sandviç Kompozit plakalar vakum destekli reçine infüzyon kalıplama (VARIM) metodu kullanılarak üretilmiştir. Metre karesi 300 gr olan E-cam kumaş sıfır bölü doksan takviye malzeme olarak kullanılmıştır. Matris olarak Epoxy LY ARALDITE 1564 SP reçine ve sertleştirici Aradur 3487B kullanılmıştır. Hazırlanan numunelerin boyutu 100 mm karedir düşük hız darbe testleri uygulanmıştır. Darbe yüksekliği değiştirilerek 5kg lik kütle ile 10J dan 50Ja kadar darbe enerjisinin seviyesi elde edilmiştir.

Kuvvet-zaman, kuvvet-çökme, kuvvet-darbe enerjisi, çökme-darbe enerjisi, zaman-darbe enerjisi ve emilen enerji-darbe enerjisi, 10J, 20 J, 35J ve 50J darbe enerjisi değerleri kullanarak tasvir edilmiştir.

Anahtar Kelimeler: Sandviç Kompozit, E-cam elyaf, düşük hızlı etki, PVC köpük, iki çekirdekli.

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CHAPTER ONE
INTRODUCTION

1.1 Overview

The traditional sandwich composite consists of a core between the two thin layers. We can use sandwich composites in the different areas such as aircraft, ship hulls, land, wind turbine blades, sports industries etc, and they have specific advantages like light weight, high stiffness, acoustic damping, high strength, excellent thermal insulation, and high bending stiffness.

Impact loading affects the structural sandwich composites. So in literature, there are a lot of studies which have been focused on the impact response of sandwich composites. Impact behavior of sandwich composites is mainly affected by core and face sheet material and their thickness. Some of the studies in the following are given.

1.1.1 Experimental Studies

Jiang, Yang, Xing & Xiao (2008) used two-core sandwich composites structures under impact. They had studied two-core sandwich structures with composite laminated face sheets and a thin internal sheet subjected to low velocity impact. The results showed that the local displacement of the core was decreased. Sheer deformation in the cores of two-core sandwich structure was investigated, and it was focused on shear strains on interfaces between face sheet, internal sheet, and the cores. They had obtained that strain levels in selected elements at the interested interface depend on location of elements, and arrangements of the internal sheet.

Atas & Sevim (2010) carried out experimental investigation for impact response of sandwich composite panels of PVC foam core and balsa wood core and investigated the repeated and the single impact responses for the specimens. They used various impact energies in the experiments, and damage process was analyzed from cross-examining, load-defection curves, the damaged specimens and energy profile diagrams. After that they observed damages like fiber cracks at the top and bottom face sheets, delamination between glass and epoxy, and shear fractures.

The investigation of the effects of a small mass impact on the sandwich composites plates was studied (Christopherson, Mahinfalah, Jazar, & Aagaah, 2005). They used foam-filled honeycomb cores that resisted against to small mass impacts. Carbon fiber was used as reinforcement in the skins. They investigated the effect of different laminate configuration during impact loading. They determined the damage by observing the degradation of strength associated with the impact event.

Gustin, Mahinfalah, Jazar, & Aagaah (2004) studied on low velocity impact of the sandwich composites plates. They used woven carbon fiber in the sandwich composites. They found maximum impact force and obtained absorbed energy data by using the impact tests on different specimens. Specimens consist of foam-filled and hollow honeycomb cores with four skins (layer), the compression after impact tests were used for determining the reduction in compressive strength by comparing impacted and non-impacted specimens.

Xiong, Vaziri, Ma, Papadopoulos, & Wu (2012) used two-layer carbon fiber in sandwich composite panels and pyramidal-core sandwich composite to study compression and impact test. The panels consist of a light and a heavy core to investigate the results of quasi-static uniform compression tests and low velocity impact. The results showed that composites with glass fiber and two-layer carbon fiber have similar specific energy absorptions and they can be used to the develop light-weight structure.

Low velocity impact was applied to the core in two-layer sandwich composite structures (Jiong & Shu, 2005). They studied normal sandwich composite structure consisting of the core between two face sheets after adding internal sheet subjected to low velocity impact on sandwich composite. They found the local displacement in honeycomb core by using various impact energy levels. Results showed that local displacement was reduced.

Gordon & Boukhili (2008) described low velocity impact test for sandwich composite. They manufactured composite sandwich which consists of PVC foam core and E-Glass/vinylester laminate skins to study impact response behavior by using drop weight impact tests. There are three types of the impact damages:

- Barely visible impact damage (BVID)
- Visible impact damage (VID)
- Clearly visible impact damage (CVID)

These types are given based on the force-time curves, and visual inspection.

The low velocity impact was studied to examine the effect of a thin soft core on impact loading (Caprino, Lopresto, Riccio, & Leone, 2012). They used two types of cores which were deferent in material nature and thickness, and they compared the results of absorbed energy, maximum contact force and perforation energy, and they found that the core affects on the material response.

Suvorov & Dvorak (2005) used compressible structural foam core between thin layers (face sheets). They used sandwich composite by using two types of interlayer materials like stiff and incompressible polyurethane (PUR) and compliant and compressible elastomeric foam (EF), together with the same face sheet and core materials. These materials were subjected to low impact velocity. The results show that PUR interlayer decreases both overall and local deflections of face sheet and local compression of the core.

Shyr & Pan (2004) investigated damage characteristics and fracture models using a camera. They conducted impact of samples which have two different types of fabric; hollow of core glass fabric and nonwoven mat subjected to impact loads. Both the hybrid laminate and sandwich laminate had delamination and damage. They found that impact behavior and damage characteristics are affected by inlaid materials.

Evci & Gulgec (2011) used three types of composites in the experiment, woven E-glass, woven Aramid and unidirectional E-glass. Low velocity impact tests were carried out to investigate rebounding, penetration and perforation situations for the composites. Energy profile diagram for unidirectional E-glass and weave E-glass are found. They obtained that strength under dynamic loading increases considerably compared to static loading.

Wet lay-up was used to make 3D glass reinforcements (Cao, Qian, Wei, & Li 2010). They used four types of 3D specimens glass fiber woven fabric-reinforced composites and all the sandwich filling by epoxy resin, they investigated the impact characteristics as time to load, peak load and absorbed energy. Images were used to analyze the impact damage.

1.1.2 Numerical Studies

Bending of sandwich composite was analyzed (Kheirikhah, Mohammad, Khadem, & Farahpour 2012). They used three dimensional finite element methods, elastic core and two skins (with shape memory alloy wires) to analyze the sandwich composite. Numerical results show bending behavior was improved by using the shape memory alloy wires in the face sheets.

Olsson (2002) investigated impact response and impact damage by using Engineering mode on the sandwich composites. Impact behavior depends on the impactor mass by using different methods.

Degree-of freedom systems were used to find the low velocity impact response of sandwich composite (Fatt & Park, 2001). They obtained deformation response and impact damage of the sandwich composites. They compared values for three freelance studies of experiments with analytical predictions in the impact force.

Apetre et al. (2006) carried out low velocity impact response of the sandwich composites. The core was functional with different thickness and density to make the sandwich panels. They used Fourier series and Galerkin's method to solve two-dimensional elasticity equations. Sandwich panel was assumed quasi-static. Results show that the contact stiffness increases for the beam with graded core resulting in the contact stresses and other stresses.

Qiao & Yang (2005) have studied on the elastic method for nonlinear impact response of sandwich composite. Effects of the elastic half-space and the anti plane core, contact force and maximum deflection were shown. They used LS-DYNA finite element program to obtain theoretical model and to find the impact and static behaviors for the sandwich on the solid half space. They found damage size, damage position by using maximum deflection and peak contact force.

1.1.3 Experimental and Numerical Studies

Composite sandwich plate was used to study dynamic response by a rigid ball (Lee, Huang & Fann, 1993). They put two separate plates however the core had transverse shear and normal stiffness to find deformations under load of two faces. The finite element methods were used to discretize the sandwich plate in the numerical study. The results of dynamic strain theoretical analysis were compared with strain gage measurement ones.

Karahan, Gul, Lvens & Nevin (2012) used four types of core thicknesses of 3D-sandwich with and without foam filling between the face sheets with same fabric densities to study impact damage in the sandwich composites and low velocity impact properties. They used 32J and 48J energy levels to conduct impact test. Time to load, peak load, absorbed energy and energy to load were found. They also analyzed the compressive strength and impact damage.

The results were given for both numerical study and experimental study of sandwich panels subjected to low velocity impact by Wang, Waas, & Wan, (2013). They used hemispherical steel impactors with different diameters and different energies. They adopted digital image correlation for measuring real-time displacement, velocity for the impactor and deflection time history at bottom skin. They applied some methods (destructive sectioning and non-destructive inspection) to determine the internal and external damage on the sandwich composite subjected to low velocity impact. They based their calculations on the Schaprey theory to find the nonlinear contact for woven carbon laminates when applying impact, 3D finite element methods were used to resolve the impact response at the damage.

The numerical results of sandwich composites subjected to low velocity impact was compared with experimental tests by Rajaneesh, Sridhar, & Rajendran, (2012). The specimens in used experiment consist of core material between face sheets with two types of ductile aluminum and brittle carbon fibers for sandwich plates. In numerical study, 3D finite element method was used to find energy absorption-time and contact force-time histories.

Navarro, Marguet, Ferreo, Barrau, & Lemarie (2012) have studied modeling the impact on layers (skin) of the Helicopter blade, experimentally to correct numerical results of the behavior of the layer for a static test and low velocity impact test.

Wang, Wu, & Ma (2009) have investigated low velocity impact (LVI) response of carbon fiber composites, experimentally and they found new damage style in the composite plates by using drop-weight machine. ABAQUS was also used in numerical analysis by 3D finite element model to find the damage problem and peak loading.

Khalili, Khalil Smr, & Amidpour (2012) studied on improving absorbed energy and design of structures of composite materials. ABAQUS FE software was used for modeling sandwich structure. They used metallic foams and polymeric foams in composite sandwich to improve absorbed energy capacity. They manufactured sandwich composite by using different types of the core and skins to conduct experiments: Finally, they calculated internal energy and displacement of sandwich composites subjected to low velocity impact.

Malekzadeh, Khalili, & Mittal (2007) have investigated low velocity impact behavior of composite sandwich panel by using flexible core between face sheets to find contact between composite sandwich panels and the impactor. Three-degrees-of freedom was used to model the interaction between the impactor and panels. IHSAPT theory and Galerkins method were used and they compared the numerical results with experimental ones.

1.2 The Thesis Objectives

In this thesis, the investigation of the impact behavior of the sandwich composites has been done, by comparing:

- Effect of the core material thickness on the impact behavior of the sandwich composites, by using the traditional sandwich composites which consist of different PVC core thickness like 5mm, 10mm and 15mm between top 3-layer and bottom 3-layer.

- Effect of the number of pieces of core material with variable thickness on the impact behavior of the sandwich composites, by using sandwich composites which consist of different PVC core thicknesses and pieces like 5mm, 5/5mm and 5/5/5mm and totally six layers at top and bottom, one-internal sheet in two cores and two-internal sheet in three cores, respectively.

- Effect of the core material number with equal thickness on the impact behavior of the sandwich composites by comparing:

  - the traditional sandwich composites which consist of one PVC core with 10mm thickness and 3-layer at top and 3-layer at bottom, and the second sandwich composites which consist of two-PVC core with 5/5mm thickness and 2-layer at top and 2-layer at bottom, one-internal sheet with 2-layer.

  - the traditional sandwich composites which consist of one PVC core with 15mm thickness and 3-layer at top and 3-layer at bottom, and the second sandwich composites which consist of three-PVC core with 5/5/5mm thickness and 2-layer at top and 2-layer at bottom, two-internal sheet with 1-layer each other.

The specimens of the sandwich composites were subjected to low velocity impact (LVI), experimentally. As an example, traditional sandwich composite which consist of PVC with 5mm core thickness for 10J impact energy was modeled and impact analysis was made by LS-DYNA. Contact force – time, contact force–deflection, contact force–impact energy, deflection- impact energy, time-impact energy, and absorbed energy-impact energy diagrams have been drawn for each impact energy level; 10J, 15J, 20J, 25J, 30J, 35J, 40J, 50J .

CHAPTER TWO
SANDWICH COMPOSITES AND IMPACT PROPERTIES

2.1 Introduction

Composite material means two or more materials are combined to obtain better properties (Kaw, 2006). The final properties of composite material are better than constituent material properties. There are more than 50000 materials available to use for design and manufacturing for products of different applications. Composite material consists of a matrix and reinforcement, properties and the structure of matrix-fiber play a major role in the mechanical and physical properties of composite material. Matrix can be metals, plastics or ceramics. The reinforcement used to improve performance, can be particulates, whiskers or fibers, and the fibers may be continuous, discontinuous, long or short depending on the application and manufacturing process.

2.2 Sandwich Composites

Traditional sandwich composites consist of a core between two face sheets (skins) as shown in the Figure 2.1. The principal properties of sandwich composite are:

- Light weight
- High flexural rigidity
- Excellent thermal insulation characteristics

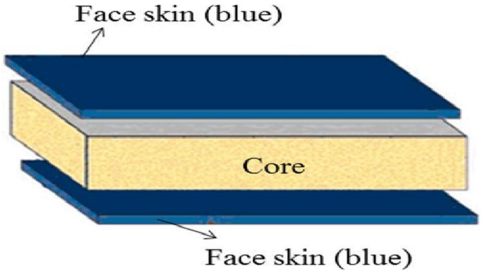
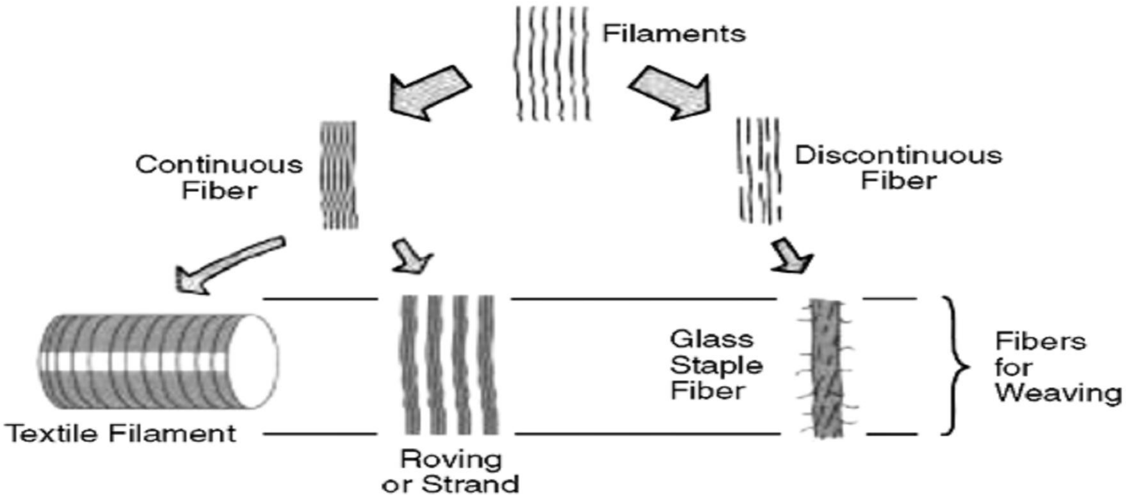


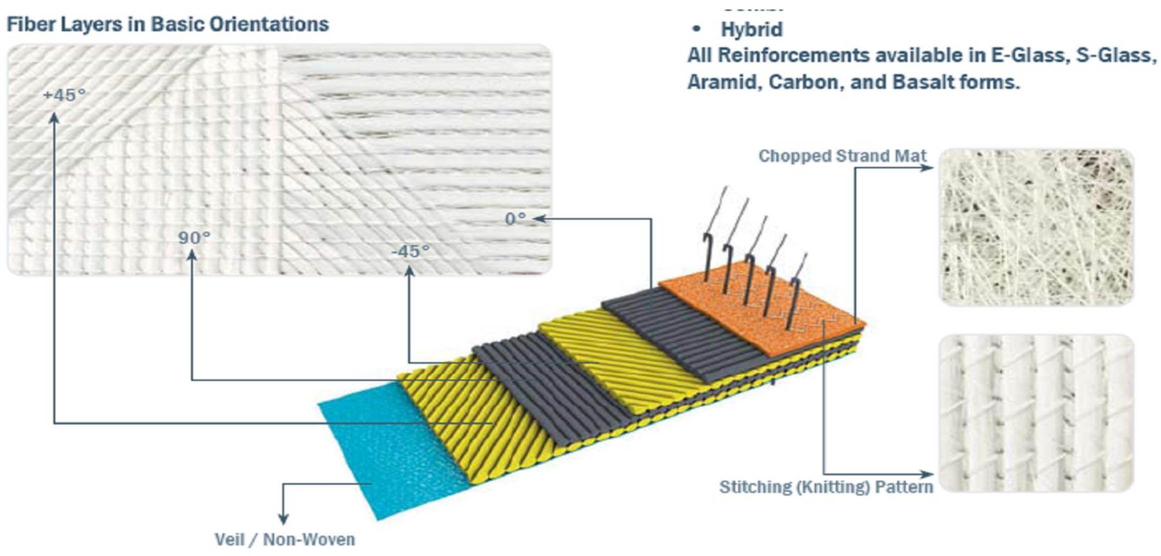
Figure 2.1 Sandwich composites. (Konka, Whap & Lian, 2011)

2.2.1 Face Sheets

Face sheet is made of fibers which consist usually of thousand filaments having diameters between 5 to 15 micrometers. Face sheet can be glass, aluminum, aramid or Kevlar (very light), carbon (high modulus or high strength), boron (high modulus or high strength) and silicon carbide (high temperature resistant). Figure 2.2.a explains different fiber forms for glass fiber. There are three types of glass fibers, E-glass, S-glass, and C-glass.



(a)



(b)

Figure 2.2 (a) Schematic illustration of different fiber forms for glass fiber (Daniel Gay, 1997) (b) orientation of fiber layer for E-Glass. (Atas, nd)

2.2.2 Core Material

The core provides the necessary shear strength to the structure. The core material is normally a low strength material, but its higher thickness provides the sandwich composite higher bending stiffness and overall lower density. Figure 2.3, there are four types of the core:

a- Corrugated core
b- Foam or solid core
c- Truss core
d- Honey comb core

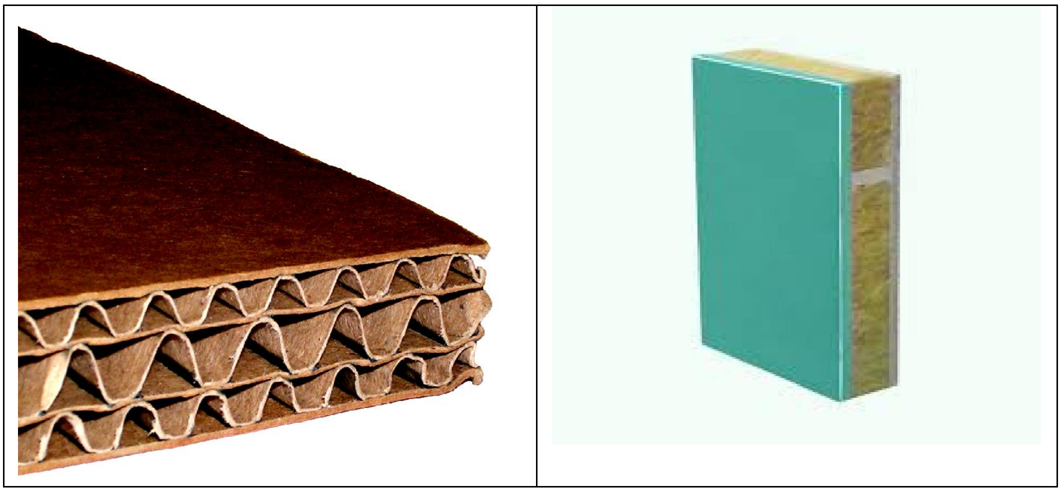
The most widely used among the foams or solid core;

- Polyvinyl chloride (PVC)
- Polystyrene (PS)
- Polyurethane (PU)
- Polymethyl methacrylamide (acrylic)

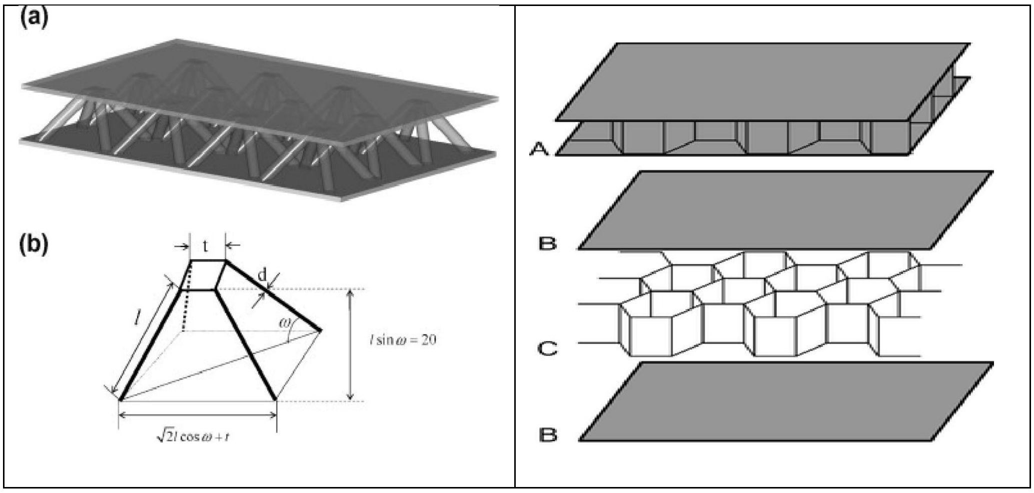
The general weight and thickness of the used foam cores are in the range of:

Weight: 30 – 300 kg/m^3

Thickness: 5 – 50 mm



(a) (b)



(c) (d)

Figure 2.3 Sandwich composite with with (a) Corrugated core (Metawell, nd) (b) Foam or solid core (Directindustry, nd). (c) Truss core (Google, nd) (d) Honey comb core (Wikipedia, nd).

2.3 Resin

Sandwich composites consist of core between two layers (reinforcing fibers) and matrix materials. The matrix materials shall have lower modulus and greater elongation than fiber. The matrix wraps on the fiber. There are two types of resin:

2.3.1 Thermoset Resin

Thermoset resin consists of molecular chains (cross linking) which are not flexile, and cannot be remelted or reshaped, the most widely used types of thermoset resins are:

- Polyester
- Vinyl ester
- Phenolics
- Polyurethane
- Epoxy

Liquid epoxy with a hardener is used to manufacture sandwich composites and after adding the hardener it is observed that cross-links grow in three dimensional and, finally epoxy resin becomes solid. There are three types of epoxy:

- Liquid

- Solid
- Semi-solid

2.3.2 Thermoplastic Resin

Thermoplastic resin do not have a cross link so they can be reshaped and flexile. The most widely used types of thermoplastic resin are;

- Nylons
- Polypropylene (PP)
- Polyetheretherketone (PEEK)
- Polyphenylene Sulfide (PPS)

2.4 Composite Manufacturing Processes

There are several methods to produce sandwich composite, the most widely used methods are:

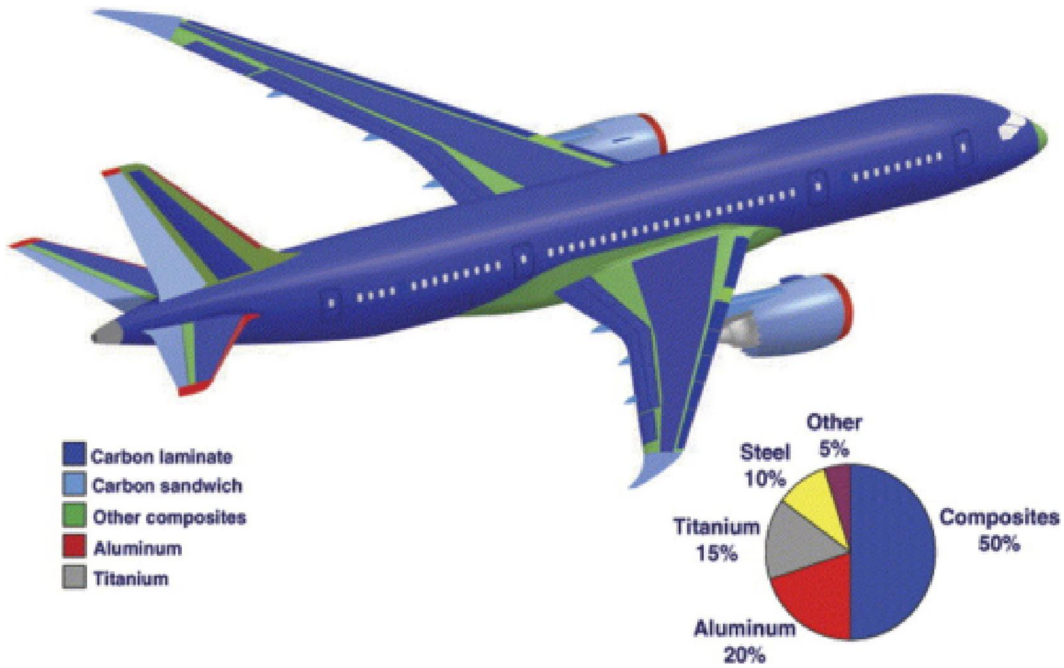
- Vacuum Assisted Resin Infusion Molding Process (VARIM)
- Resin Transfer Molding (RTM)

And both of these methods use liquid epoxy resin to fill dry fibers that are as layers. The resin viscosity has to be low in order to permit resin flow through layers (skins).

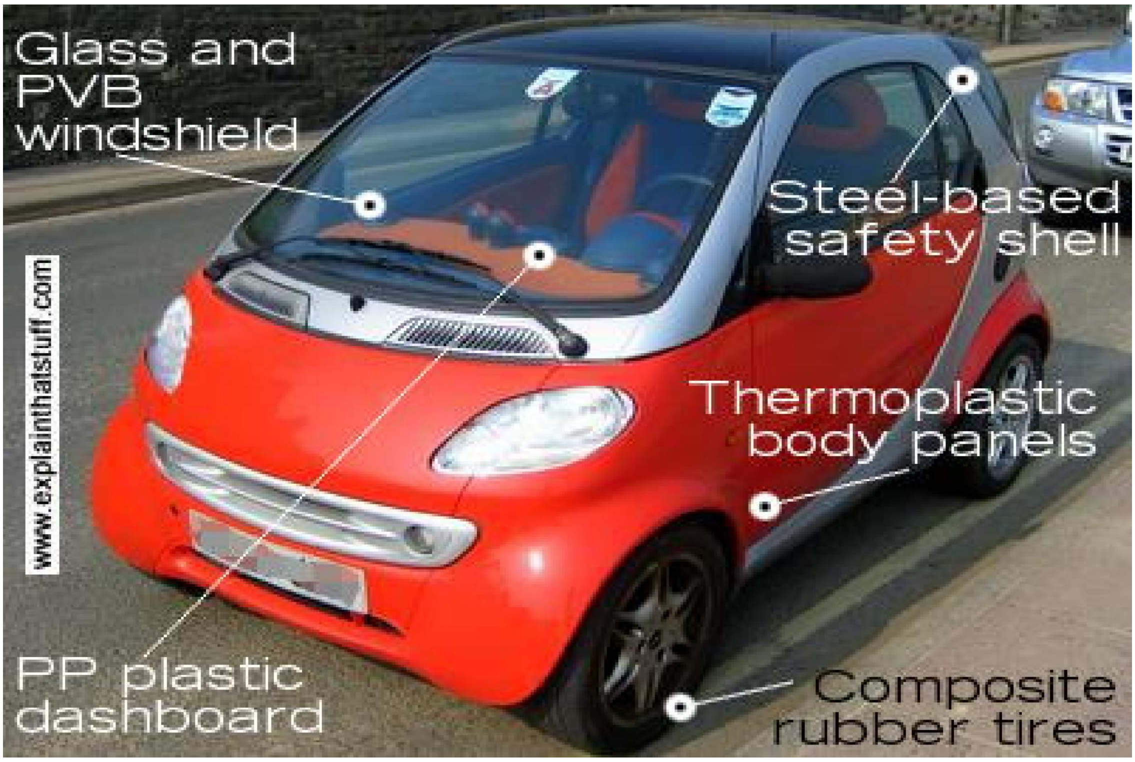
For production any part of sandwich composite, it is needed to have:

1. Raw material
2. Tooling/mold
3. Heat
4. Pressure

In this study, sandwich composite is manufactured using Vacuum Assisted Resin Infusion Molding Process (VARIM). This method can be used in the manufacturing of small boats, train, wind turbine blades, truck bodies, hulls of yachts, cars, spacecraft structures, bridge decks, sailboats military ground infrastructure etc. Figure 2.4 shows some examples of such composite structures.



(a)



(b)

Figure 2.4 Examples of sandwich composite structures (a) (Cnde, nd) (b) (Explainthatstuff, nd)

2.5 Impact Properties of Sandwich Composite

The impact or shock loading refers to dissipate energies and capacity to absorb by sandwich composite (Abrate, 2011). There are three types of the impact response of materials as given below:

- Low velocity impact (LVI) as well knows as large mass impact velocity which generally occurs at velocity below 10 m/s.

- Intermediate velocity impact is between low velocity impact and, high velocity impact. Intermediate velocity impact occurs from 10 m/s to 50 m/s.

- High velocity impact is also known as small mass velocity impact or ballistic impact and it usually produce by small arms fire or explosive fragments. High velocity impact occurs between 50 m/s to 1000 m/s, this hyper velocity impact is being bigger as 2 km/s to 5 km/s.

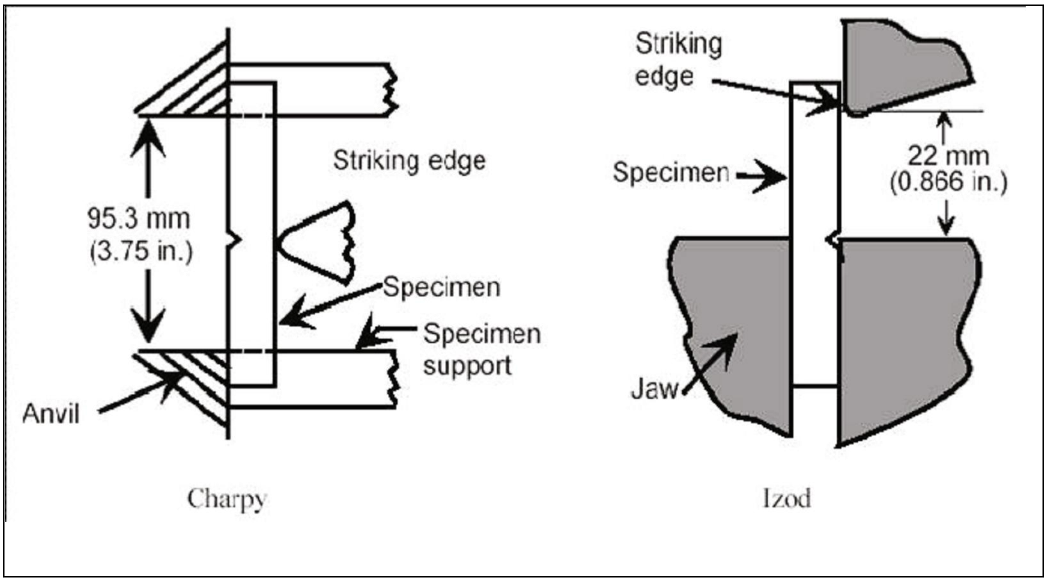
This type of impact is commonly studied in the context of developing protection against micrometeorites of objects and personnel in low earth orbit. Impact properties are affected by fiber length, impactor type and, geometry and residual strength.

2.5.1 Charpy and Izod Impact Method

Both Charpy and Izod impact methods use a swinging pendulum (Figure 2.5). Specimens have a notch on the tension side. The notch works as a stress concentration site to lower the energy wanted for the beginning of fracture.

A horizontal simple supported beam specimen is used in Charpy method however the specimen is placed to be the vertical cantilever in Izod method.

These methods are used in order to compare the impact response of isotropic material which is manufactured by different processing conditions. The fracture phenomenon is complex for polymer composites, and these methods may not be adequate in order to represent a realistic impact condition. Impact energy in carbon and boron fiber- reinforced epoxies is lower than many metals.



(a) (b)

Figure 2.5 (a) Charpy impact test (b) Izod impact test. (Abrate, 2011)

2.5.2 Drop-Weight Impact Test Systems

The Energy is used to break a beam or a plate specimen by using drop-weight impact test which has free fall of known weight. Weights are added to provide the desired impact energy; the kinetic energy of the falling weight is calculated by changing its drop height. The impact energy is measured depending on the ratio of beam length to effective depth. The specimens are mounted as simply supported or fixed. Then the specimens are subjected to impact load, the impact load is measured by load cell. For investigation of material response against impact in general planar laminate is used.

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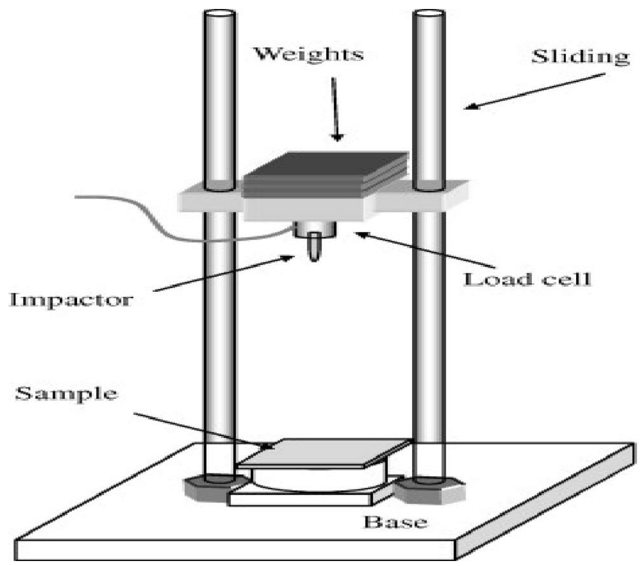


Figure 2.6 Schematic arrangements for a drop-weight impact test (Google, nd).

2.6 Failure Modes in Low Velocity Impact

The failure occurs in the laminates by using low velocity impact. There are four failure modes (Abrate, 2011):

- matrix cracking
- debonding or delamination
- fiber failure
- penetration

The interaction between failure modes influences initiation and propagation of damage.

2.6.1 Matrix Cracking

Matrixes cracking begin in upper layers after the contact of the impactor and lowest damage can be visible between 1J to 5 J by using low velocity impact energy (LVI). There are two types of matrix crack, tensile cracks and shear cracks.

Matrix cracking is usually parallel to fibers direction because the tension, compression, shear and matrix cracking depend on the global characteristics of the impacted specimen. Shear cracks are formed in the material because of the high transverse shear stress of low velocity impact. Tensile cracks occur when in-plane stresses over comes the transverse strength of the ply. Matrix cracks occur in the lowest layer for the thin laminate because of the bending stresses in the back side of the laminate.

2.6.2 Debonding or Delamination

Delamination occurs between plies as a result of interlaminar stresses. It means separation of plies that progress in the resin rich area between adjacent layers. Bending stiffness mismatch between adjacent layers is resulting in delamination. The delamination area is generally oblong shaped with its major axis being coincident with the fiber direction of the layer below the interface. For fiber reinforcement of 0/90 delamination is being peanut shaped damage. Material properties, stacking sequence and laminate thickness affect the delamination.

2.6.2.1 Delamination Initiation and Interaction with Matrix Cracking

Delamination occurs due to transverse impact after threshold energy has been reached and delamination progresses at adjacent interface. Matrix cracks and high interlaminar shear stresses occur because of the high out-of plane normal stresses at interface. Delamination caused by shear cracks is unstable while delamination which consists of bending cracks is stable.

2.6.2.2 Growth of Delamination

The energy absorption for growth of delamination is found constant. The peak impact force can be predicted from the interlaminar fracture toughness and it does not depend on delamination size or delamination area.

2.6.3 Failure of Fiber

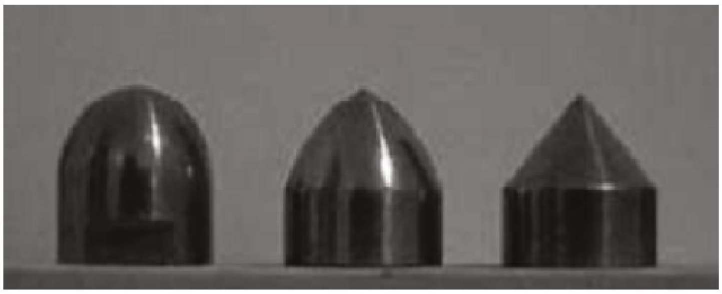
Failure of fiber occurs after matrix cracking and delamination in the case of low velocity impact (LVI) on sandwich composites. High stresses and indentation effects cause the failure of fiber just where the impactor (striker) contacts. Failure of fiber at non-impacted face also occurs because of the high bending stresses.

2.6.4 Penetration

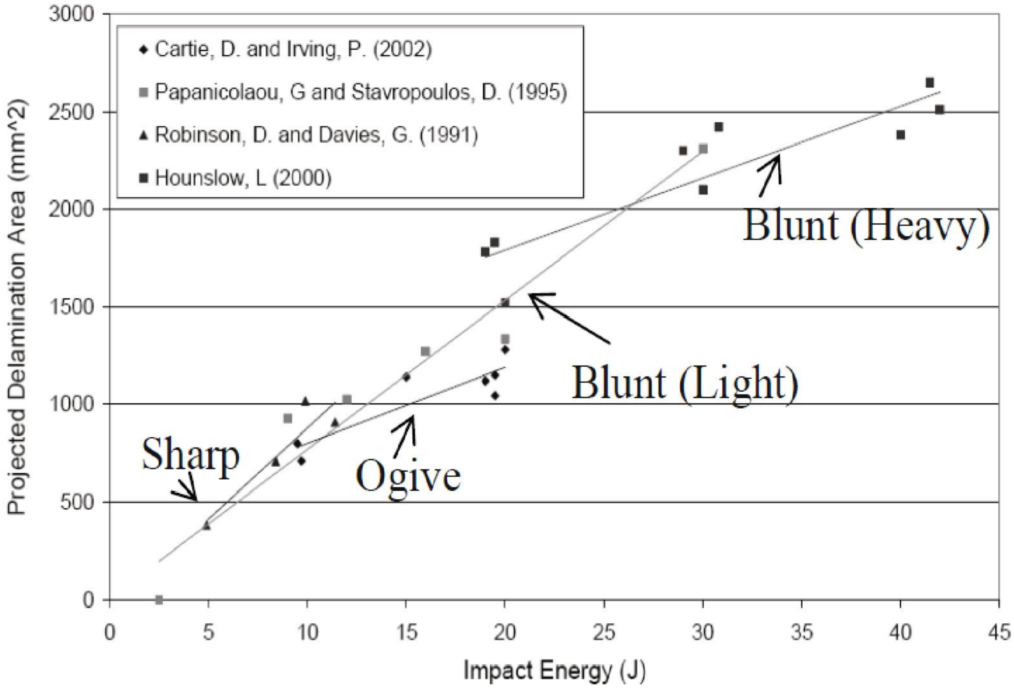
Penetration is a type of failure and it occurs after failure of fiber which is caused by impactor. The thickness of the specimen affects penetration, delamination, shear-out and elastic flexure; which are major forms of energy absorption during laminate penetrations. Penetration process is affected by fiber sizing, fiber orientation, tow size, matrix type, weave structure and interface.

2.7 Geometry and Mass of Impactor

The response of the specimen depends on the impactor shape, size, material, mass and angle of falling. Figure 2.7 shows different impactors and variations of delamination areas by using different impactors. The fiber damage occurs because of the sharp impactor which consists of more surface while internal delamination occurs because of the blunt impactor.



(a)



(b)

Figure 2.7 (a) different shape of impactor (hemispherical, pointed, ogive) (Abrate, 2011) (b) delamination areas by using different shape of impactor with low velocity impact response (Abrate, 2011).

2.8 Low Velocity Impact of Sandwich Composite

The sandwich composites consist of the core which is low density, lightweight with high thickness and two faces that have high modulus, and high strength. The impact damage in the sandwich composite depends on the projectile shape, material and geometric properties for the core and layers (face sheet). When the layers (face sheet) are thin tensile cracking will occur and the deflection is large while if the layers (face sheet) are thick the shear cracking will occur and the deflection is small as shown in the Figure 2.8 (Abrate, 2011).

In the sandwich composite, the low velocity impact damage is as the following:

- Impactor generates the transverse shear force in the top layer (face sheet). If the layers (face sheet) resist penetration the damage is limited to the impact of side layer (face sheet). The debonding occurs between the core and layer because of the strain between them at impact point. The impactor penetrates the top layers, the core and bottom layers respectively by using higher impact energy.

- Failure of the core occurs in the form of the cell crushing. Debonding occurs between of the layers (face sheet) and the core.
- Bending on the back face occurs because of tensile forces which are acting at the back layer (face sheet) after loaded by the impactor. Debonding area is observed between the core and the back layers (face sheet) while the delamination occurs before complete penetration of the impactor at the back layers (face sheet).

(a) (b)

Figure 2.8 Low velocity impact responses with (a) thin laminate (b) thick laminate (Abrate, 2011).

CHAPTER THREE
EXPERIMENTAL PROCESSES

3.1 Manufacturing of Sandwich Composite

Vacuum assisted resin infusion molding (VARIM) was used to manufacture sandwich composite. The mold surface was covered by release film to save the mold surface from the resin through the manufacturing. After that the fabrics were put over release film and the core was placed between the fabrics for the normal sandwich composite Figure 3.1, and two-core or three-core were placed between the fabrics with internal sheet figure3.2. Then the peel ply and resin distribution medium were placed on the fabrics respectively in order to obtain suitable resin flow. Finally, to obtain a closed system, vacuum bag was used over all the surfaces. And the resin flows to dry fabrics by using the vacuum. After that, the curing process continues at 80 °C for 8 hours as shown in the Figures 3.1-3.

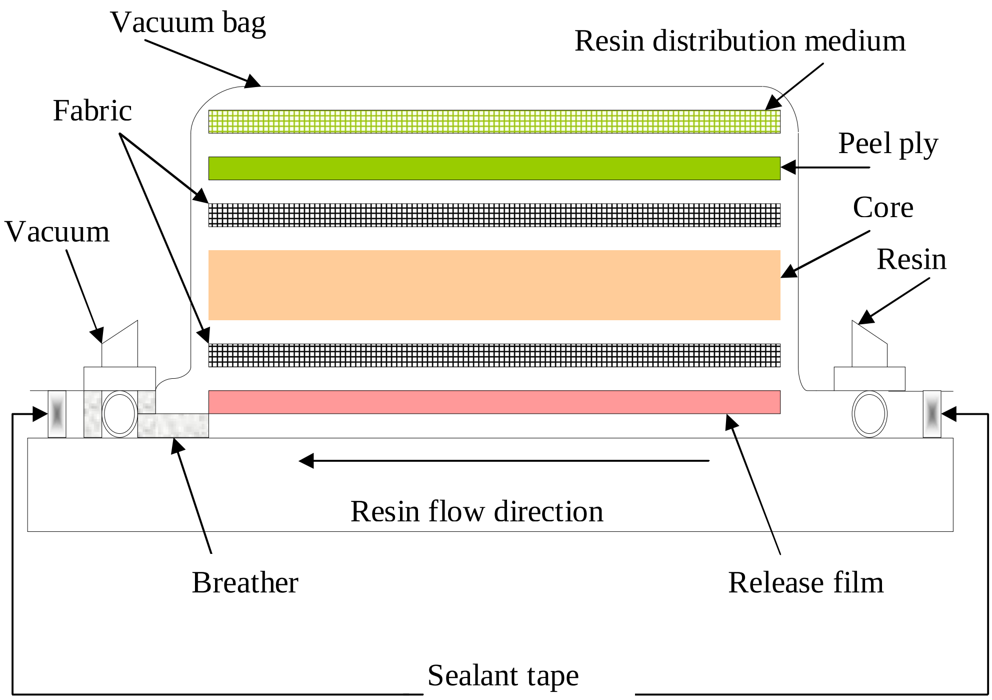


Figure 3.1 Vacuum Assisted Resin Infusion Molding Process for the traditional sandwich composite

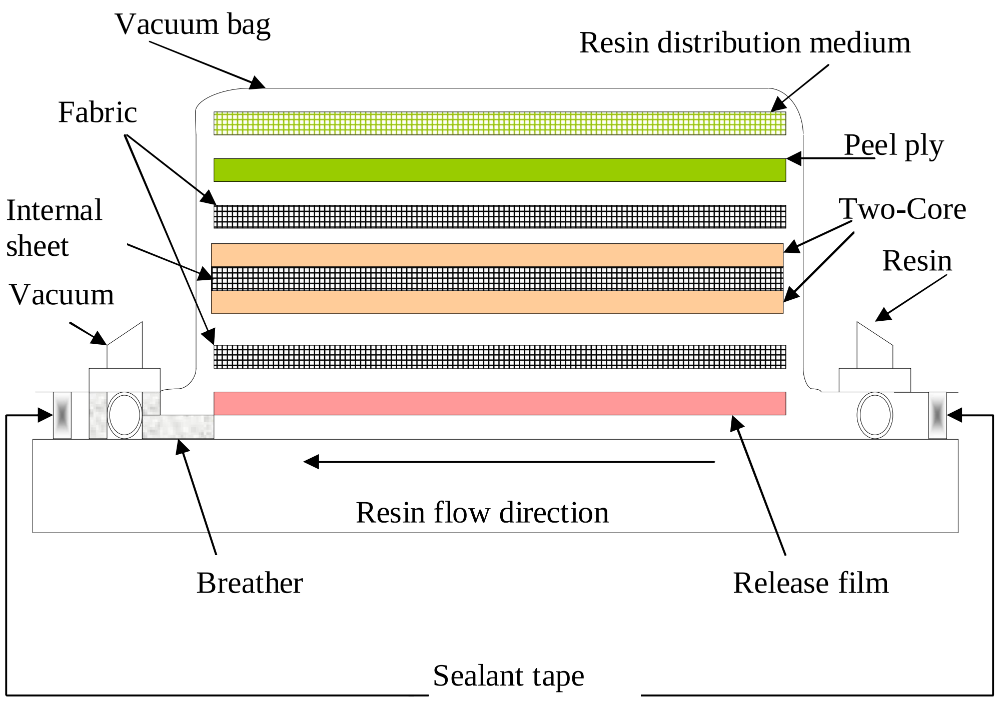


Figure 3.2 Vacuum Assisted Resin Infusion Molding Process for sandwich composite with two-core and internal sheet.

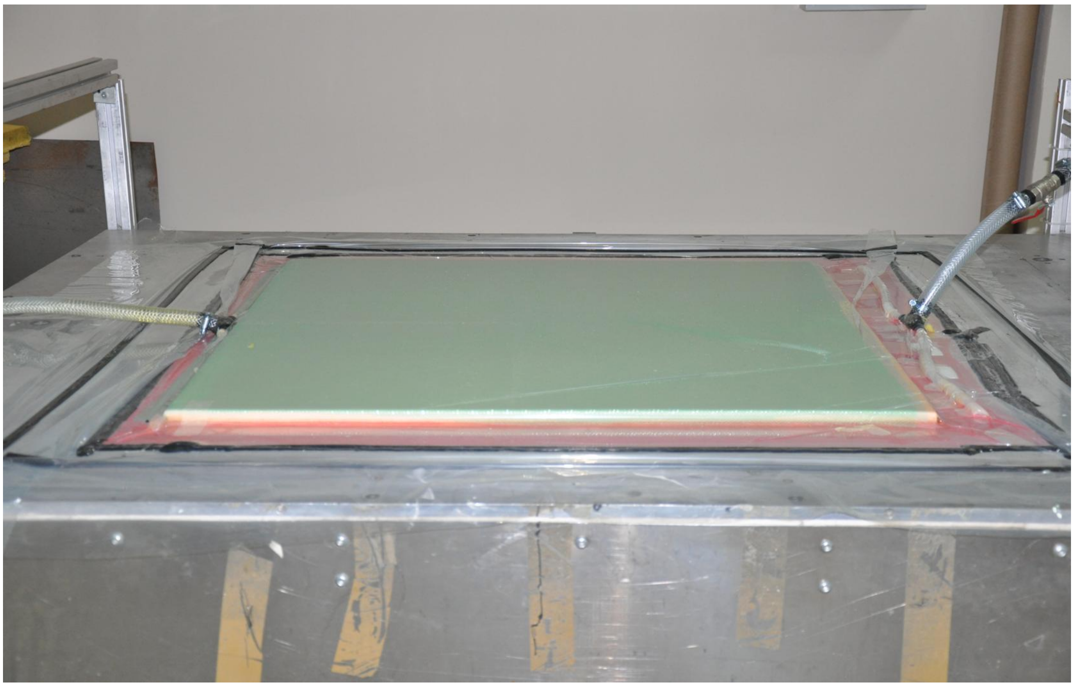


Figure 3.3 Photo of the sandwich composite during fabrication.

The insulation material is used to minimize heat transfer from upper face of the sandwich composite during process as shown in the Figure 3.4.

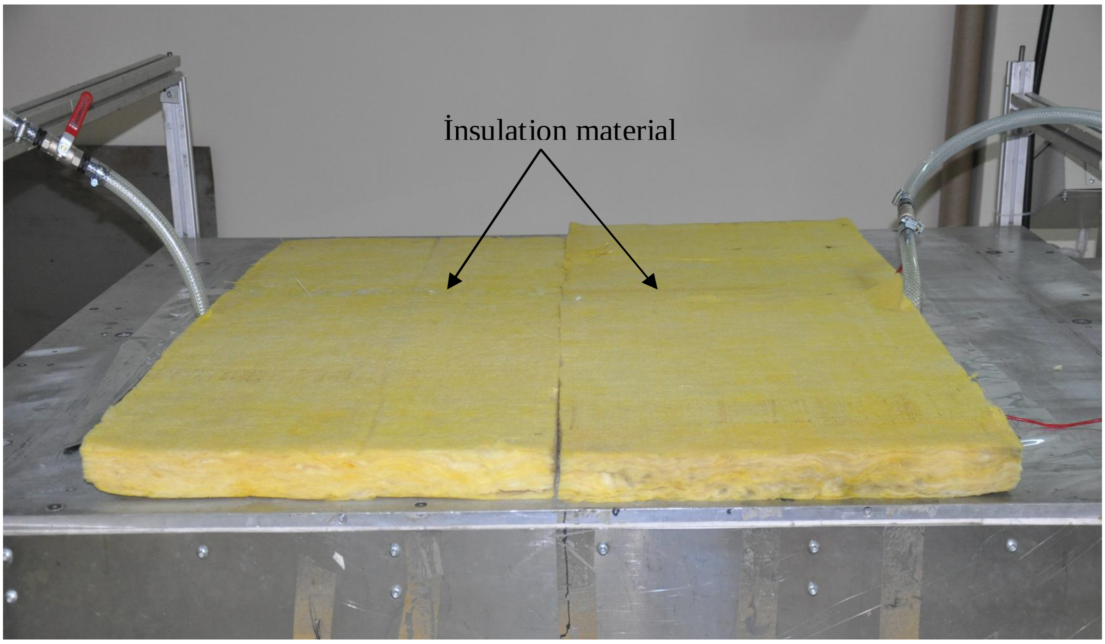


Figure 3.4 Usage of insulation material during fabrication

3.2 Properties of Material

E-glass fabrics with fiber orientation 0/90 having density of 300 g/m^2 were used as the reinforcing material. AIREX PVC foam was chosen as the core material. Epoxy ARALDITE LY 1564 SP resin and ARADUR 3487B hardener were used as the matrix material. The ratio of the resin and hardener was 3/1. After mixing the resin and hardener with mixer apparatus and by the vacuum, the resin flows to dry fabrics. Stacking sequences of [0/90/0/core/0/90/0], [0/90/core/0/0/core/90/0] and [0/90/core/0/core/0/core/90/0] are orientations of the traditional sandwich composite, sandwich composite having two-core with internal sheet and sandwich composite having three-core with two-internal sheet.

Mechanical properties of composites manufactured from the reinforcement material which was used in this study have been evaluated by Ozdemir (2012) and given in Table 3.1 for information.

Table 3.1 Mechanical properties of unidirectional glass/epoxy composite (Ozdemir, 2012)

	Properties	**Magnitude**
1	Longitudinal modulus, E_1	28.60 GPa
2	Transverse modulus, E_2	10.76 GPa
3	Poisons ratio, υ_{12}	0.26
4	Longitudinal tensile strength, X_t	653 MPa
5	Transverse tensile strength, Y_t	62 MPa
6	Longitudinal compressive strength, X_c	301 MPa
7	Transverse compressive strength, Y_c	100 MPa
8	In-plane shear modulus, G_{12}	7.39 GPa
9	In-plane shear strength, S_{12}	56 MPa

We used DS-250/1300 wet cutting machine as shown in the Figure 3.5 in order to prepare the specimens. It is observed that some of the fibers are not completely wetted by the resin. Because non uniform resin distribution or viscosity increases before the mold filling is completed. For this reason, the core is drilled uniformly in order to penetrate the resin to all the fibers as shown in the Figure 3.6.

In this study, the PVC foam AIREX C.71.55 was used as the core material with different thicknesses (5, 10, 15, 5/5, 5/5/5 mm) in order to investigate energy absorption capacity of sandwich composites by using low velocity impact (LVI). All the sandwich composites were used in this thesis have been manufactured in the Composite Research Laboratory of Mechanical Engineering Department at Dokuz Eylul University in Izmir.

Mechanical properties of the core material are given in Table 3.2.

Table 3.2 Mechanical properties of the core materials (typical properties for AIREX,) (Metyx, nd)

	Typical properties for the core material		**Unit (metrical)**	**Value**	**C.71.55 PVC**
1	Density	ISO 845	Kg/m^3	Average Typ. Range	60 54-69
2	Compressive strength	ISO 844	MPa	Average Min	0.95 0.85
3	Compressive modulus	DIN 53421	MPa	Average Min	70 60
4	Tensile strength	ASTM C297	MPa	Average Min	1.5 1.0
5	Tensile modulus	ASTM C297	MPa	Average Min	42 30
6	Shear strength	ISO 1922	MPa	Average Min	0.93 0.7
7	shear modulus	ISO 1922	MPa	Average Min	21.5 18

All specimens were subjected to low velocity impact (LVI) to investigate the impact behavior of the sandwich composite by using different energies (10, 15, 20, 25, 30, 35, 40, 50) J. The specimen was prepared with the dimensions of 100x100 mm as shown in the Figure 3.7, by using wet cutting machine which has the cutting length 1350 mm and the dimensions with 2000x730x700 mm. Its properties are also given below:

- 2800 blade rpm
- Vertically adjustable and foldable mobile
- Rail pivots to a variety of angles for a perfect miter cut
- Thermal protection against current overload
- Motor assembly mounted on sliding bearings
- Retractable legs with shield function and a wheeled transportation system
- Detachable working surface for easy cleaning
- Water pump with control valve for cooling of the diamond blade
- Removable plastic water pan for easy cleanup

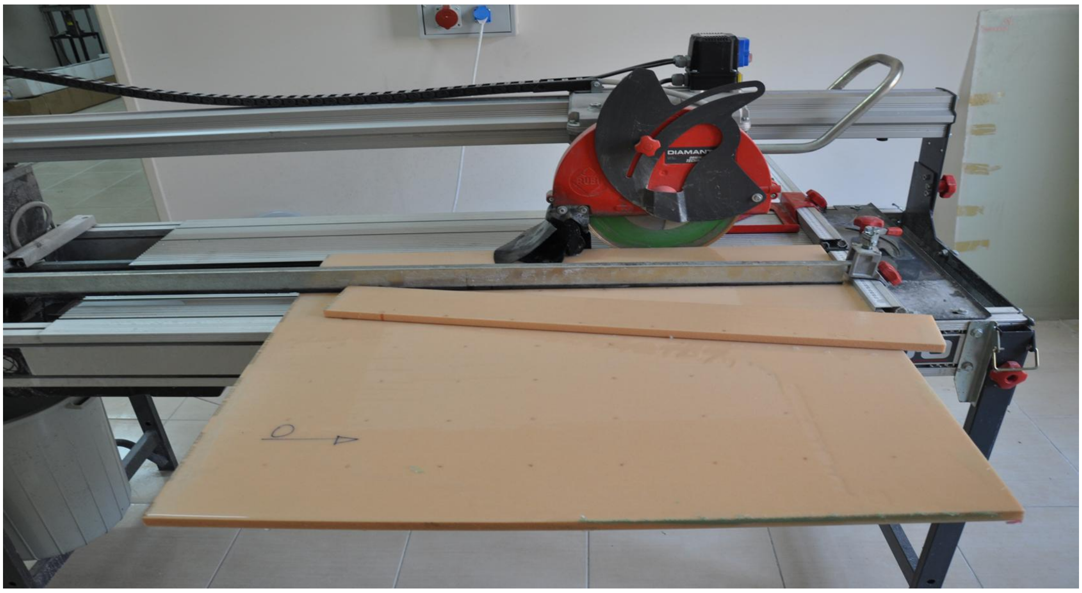


Figure 3.5 DS-250/1300 wet cutting machine.

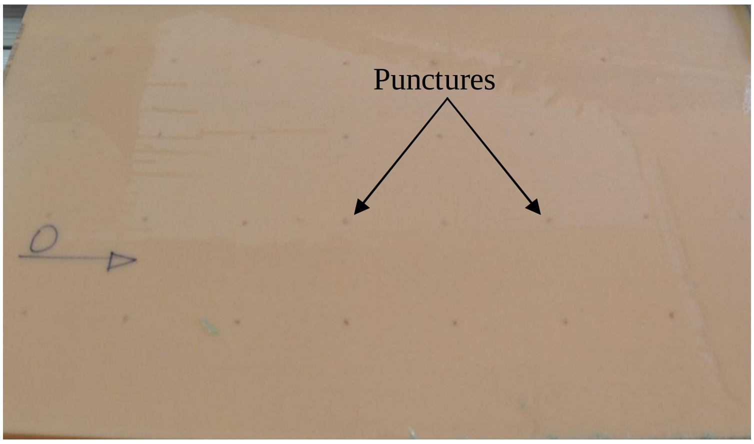
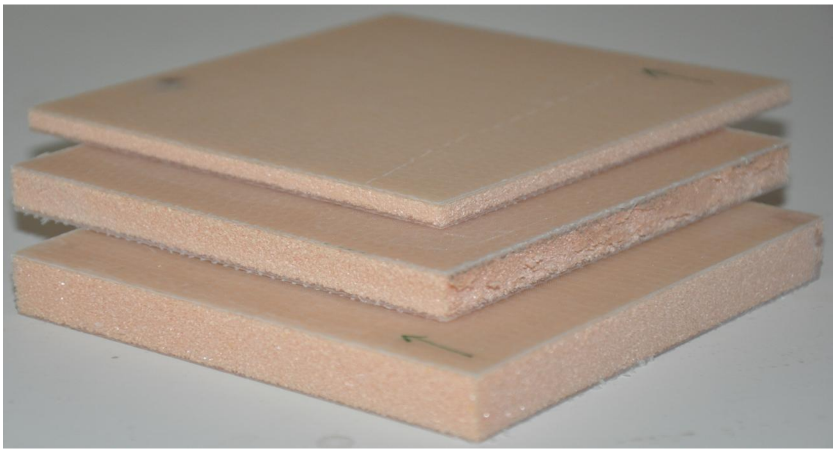


Figure 3.6 Puncture points of sandwich composites.

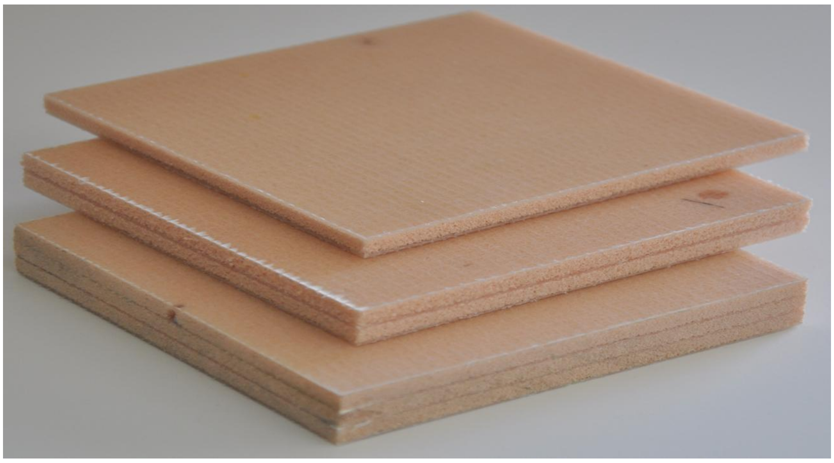
Thicknesses and weights of the specimens for each core are measured and are given in following Table 3.3.

Table 3.3 Final thicknesses and weights of the sandwich composite specimen for each core.

	Core thickness	**Thickness ± 0.05 mm**	**Weight ± 0.50 g**
1	5 mm	6.49	36.57 g
2	10 mm	11.48	39.13 g
3	15 mm	16.18	42.16 g
4	5/5 mm	11.22	42.88 g
5	5/5/5 mm	16.02	48.94 g



(a)



(b)

5mm 10mm 5/5mm 15 mm 5/5/5mm

(c)

Figure 3.7 The finished specimens of sandwich composites (a) traditional (b) multi cores (c) the finished specimens with (5 mm, 10 mm, 15mm, 5/5mm and 5/5/5mm).

3.3 Impact Testing Machine

All the specimens are subjected to low velocity impact loading by using the Fractovis Plus impact testing machine to investigate energy absorption of the sandwich composite as shown in the Figure 3.8. For this machine, the energy ranges from low to high impact energies. The specimen is mounted pneumatically by fixture of 76 mm inner diameter. The impactor has hemispherical nose, 12.7 mm diameter and mass of 5 kg. Force transducer has maximum loading up to 22.4 KN. The modes of impact for the specimens are affected by:

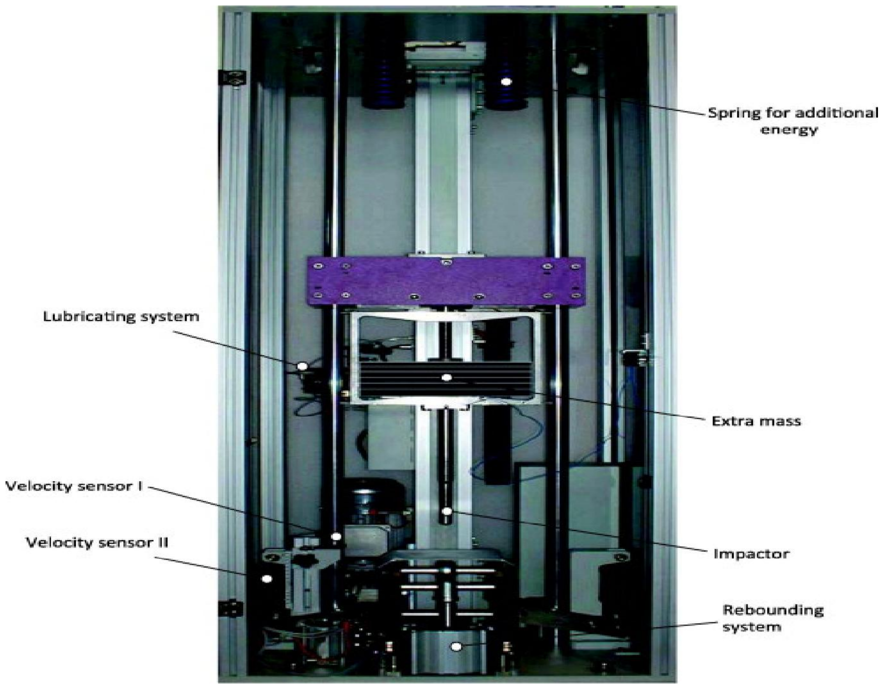
- impactor geometry
- impactor shape
- material properties
- support condition

The maximum potential energy and velocity for the drop-weigh machine is 1800 J and 24 m/s, respectively. The data acquisition system (DAS) was used to obtain data through the test, which gives 16000 data in the test.

In this thesis, different energies are chosen (10, 15, 20, 25, 30, 35, 40, 50 J) and each energy level was applied five repetitions (5-specimen per each energy level) sandwich composite for the cores of 5 mm, 10 mm, 15 mm, 5/5 mm, 5/5/5 mm thicknesses to investigate the impact behavior of the sandwich composite subjected to low velocity impact loading (LVI). The Average values and standard deviations of obtained results were calculated.

Absorbed energy versus impact energy, contact force versus impact energy, time versus impact energy, deflection versus impact energy, and contact force versus time, contact force versus deflection diagrams were plotted for each impact energy level and the results for the different specimens of the sandwich composites were compared.

(a)



(b)

Figure 3.8 (a) Ceast 9350 (Fractovis Plus) impact testing machine with data acquisition system (DAS) (b) upper part of the testing machine.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Test of Impact

Low velocity impact (LVI) tests are subjected on all of the specimens of sandwich composites which have one, two-core, and three-core with six layers by using a drop weight impact testing machine, the results show that three modes of damage processes:

- Rebounding
- Penetration
- Perforation

The contact force-deflection curves in the Figure 4.1 are shown to explain the difference between the three modes of damage. The damage growth is determined by increasing the impact energy which is known as the energy applied on the specimens of the sandwich composites. Rebounding case becomes Penetration and Perforation cases, respectively.

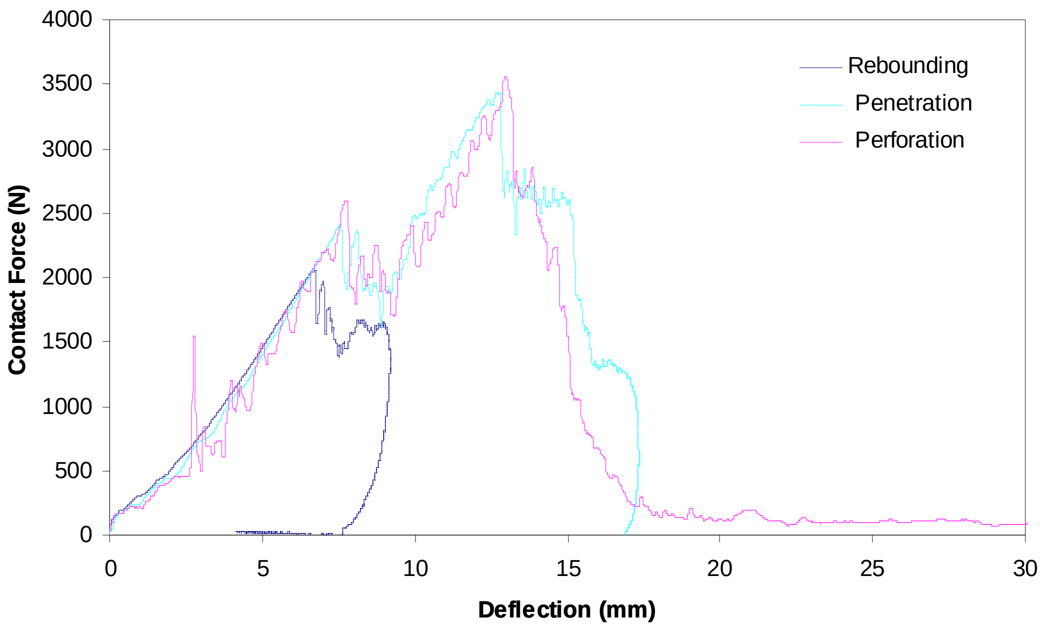


Figure 4.1 Contact force-deflection curves.

The most important factors in impact description on the sandwich composites are (a) absorbed energy, which is defined as the energy absorbed in specimens of sandwich composites during impact test, (b) impact energy means the sum of energy applied on the specimens of the sandwich composites, (c) dissipated energy which occurs due to friction and vibration between the impactor and specimen during impact test and is smaller than identical impact energy, (d) the relationship between the absorbed energy and impact energy that explains some of the impact properties like Rebounding, Penetration and Perforation as shown in Figure 4.2.

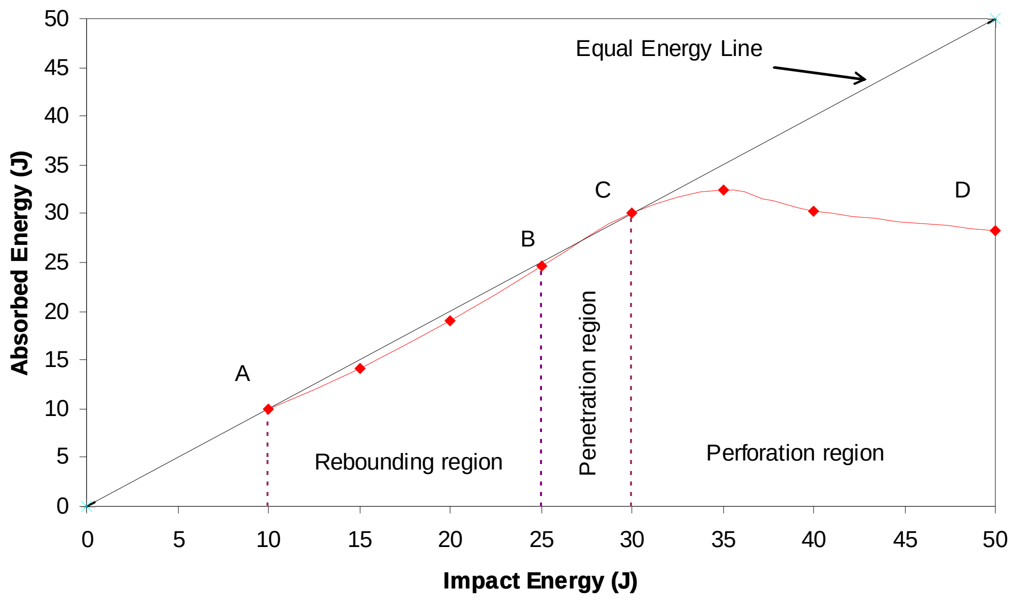


Figure 4.2 Energy profile diagram of sandwich composite.

The energy profile diagram consists of three zones AB, BC, and CD to describe the damage mechanisms over impact loading of top layers, core materials and bottom layers as shown in the Figure 4.2. AB zone explains rebounding case which is being under the equal energy line. The excessive energy is retained in the impactor and used to rebound the impactor from the specimen at the end of an impact event, and by increasing impact energy impactor moves from AB to BC after perforating of top layers (shattered E-glass mat).

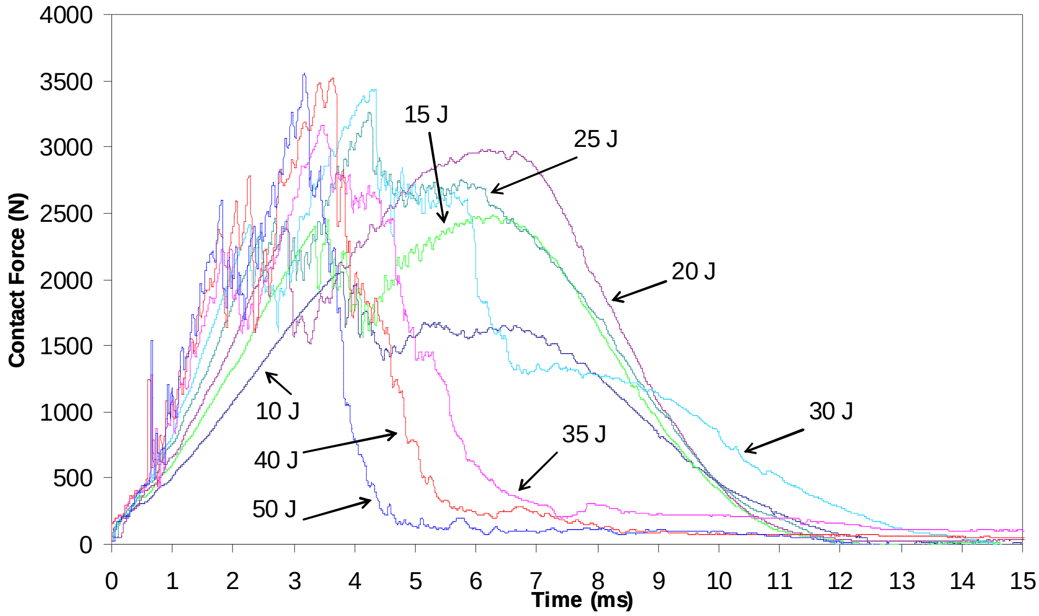
BC zone represents the penetration case and in this zone the impact energy is absorbed by the specimens and the impactor shocks the specimen with out rebound.

CD zone shows perforation case, which occurs by increasing impact energy, the perforation is beginning at point C. The impactor reaches to the bottom layers and rebound after shocks the specimens of sandwich composites and causing the damage at top, core and bottom layers, respectively.

Subjected specimens are manufactured of PVC foam AIREX C.71.55 with (5 mm, 10 mm, 15 mm, 5/5 mm, and 5/5/5 mm) core thickness and E-glass unidirectional fabric as reinforcement. Impactor height is various to give a level of impact energy from 10J to 50J with constant impactor mass of 5 kg. Figure 4.3 explains the relationship between contact force-time.

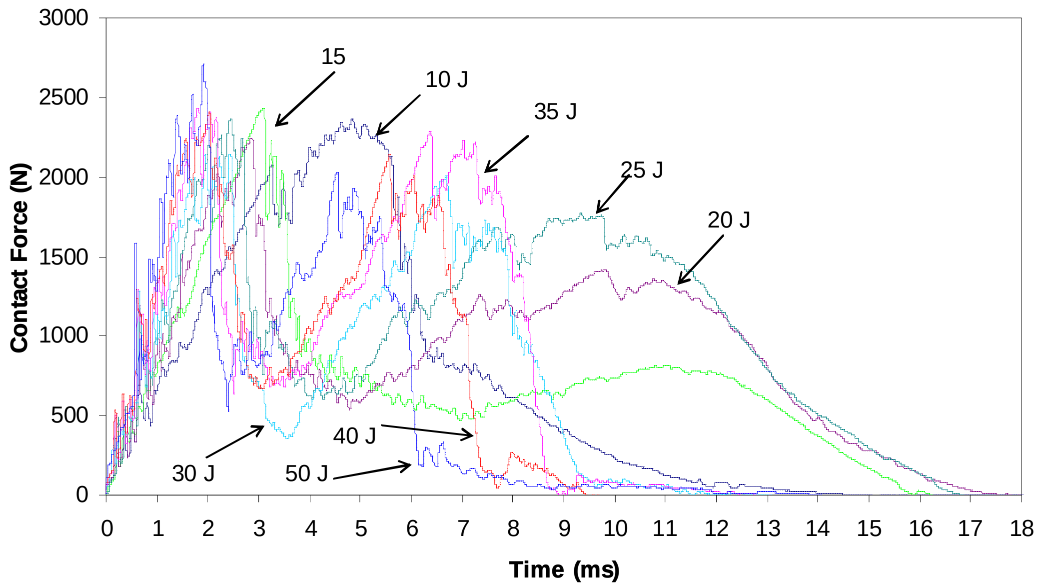
For the impact energies from 25J and higher, the transformation from rebounding to penetration, perforation takes place in a shorter time despite bigger (higher) deflection of the specimens for all types. Curves at 10J and 15J depict the rebounding case which has one peak. It is meaning that the damage at top layer as delamination and matrix cracks however the penetration case occurs by using 20J energy and perforation at 25J energy, fiber breakage and damage occur at top and bottom layers because of high impact energies, the curves have two peaks for one piece core (5mm, 10mm, 15mm) and three peaks or more for two pieces-core and three pieces-core (5/5mm, 5/5/5mm) as shown in the Figure 4.3.

The deflection represents the distance which impactor transits through impact test, and consists of closed curve and open curve. At first scenery, it is noted in Figure 4.4. The deflection increases by increasing core thicknesses for all specimens.



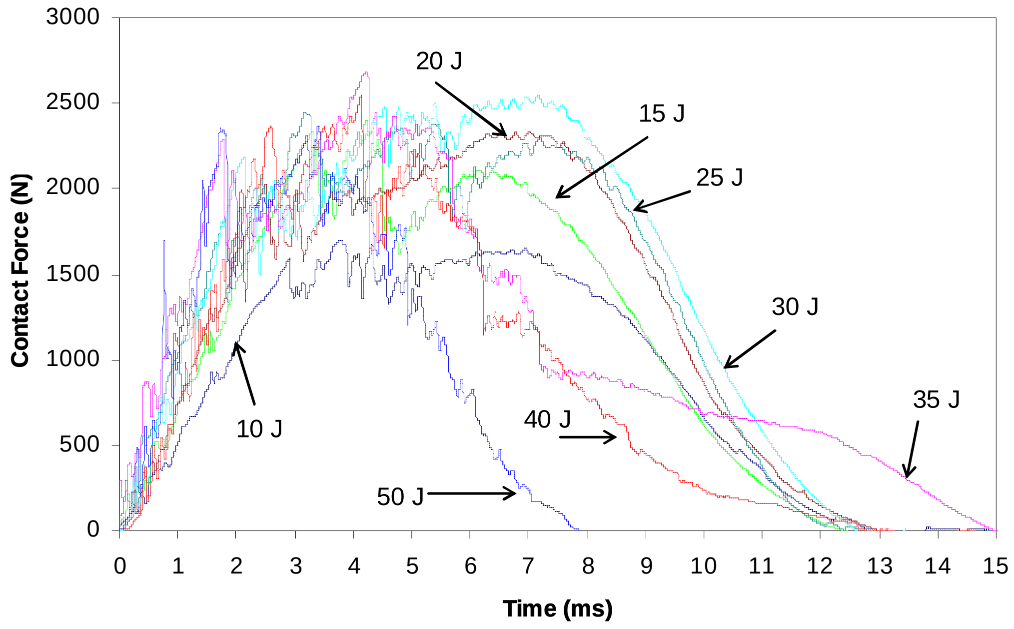
Contact Force (N)
Time (ms)
15 J
25 J
20 J
10 J
40 J
50 J
35 J
30 J

(a)

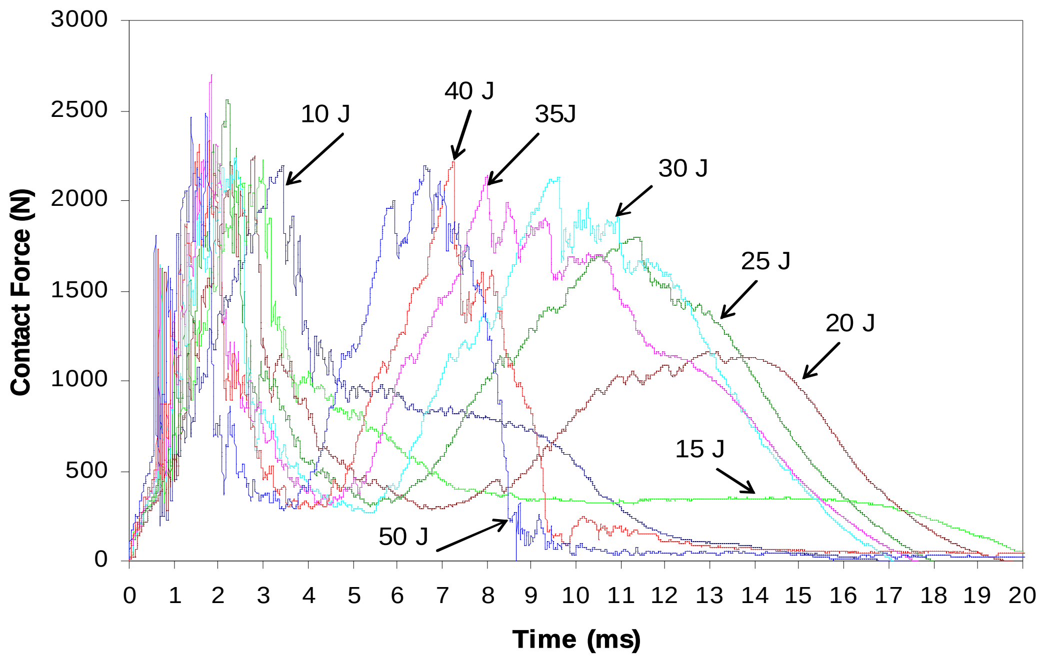


Contact Force (N)
Time (ms)
15
10 J
35 J
25 J
20 J
30 J
40 J
50 J

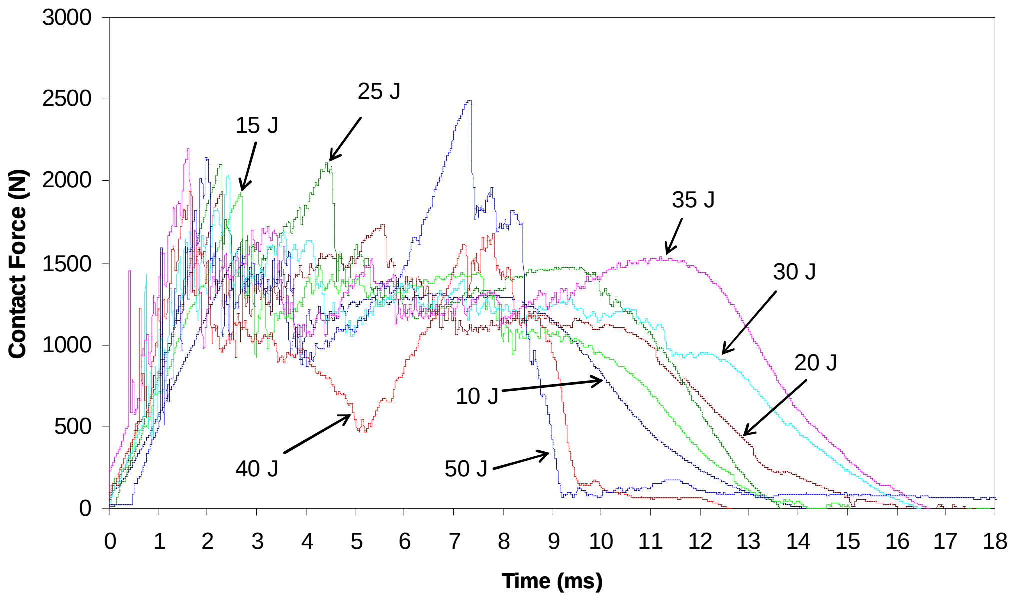
(b)


3000
2500
2000
1500
1000
500
0
Contact Force (N)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (ms)
20 J
15 J
25 J
30 J
35 J
10 J
40 J
50 J

(c)

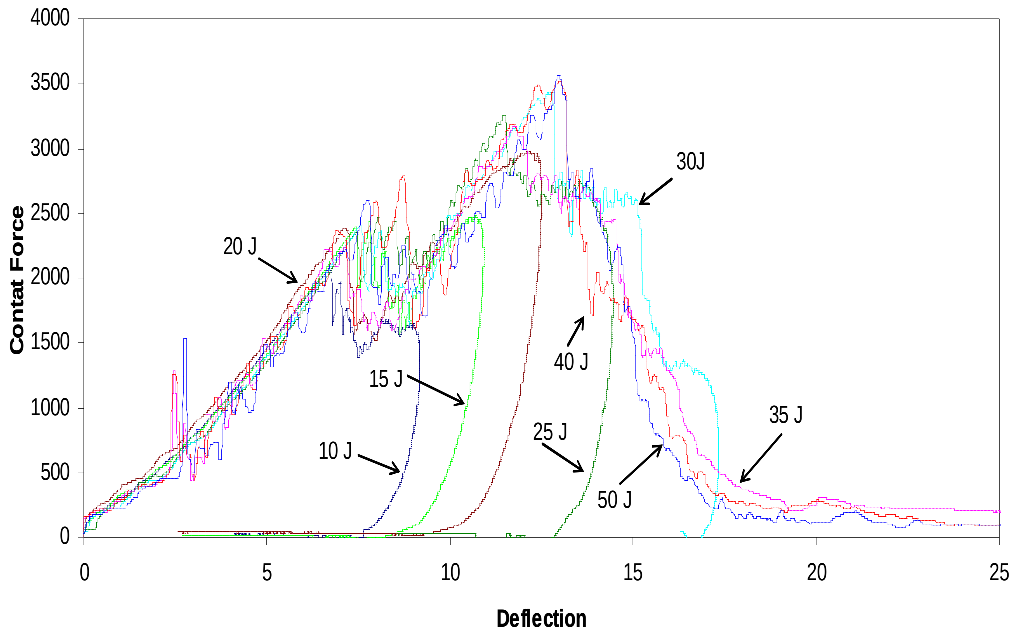

3000
2500
2000
1500
1000
500
0
Contact Force (N)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time (ms)
10 J
40 J
35J
30 J
25 J
20 J
15 J
50 J

(d)

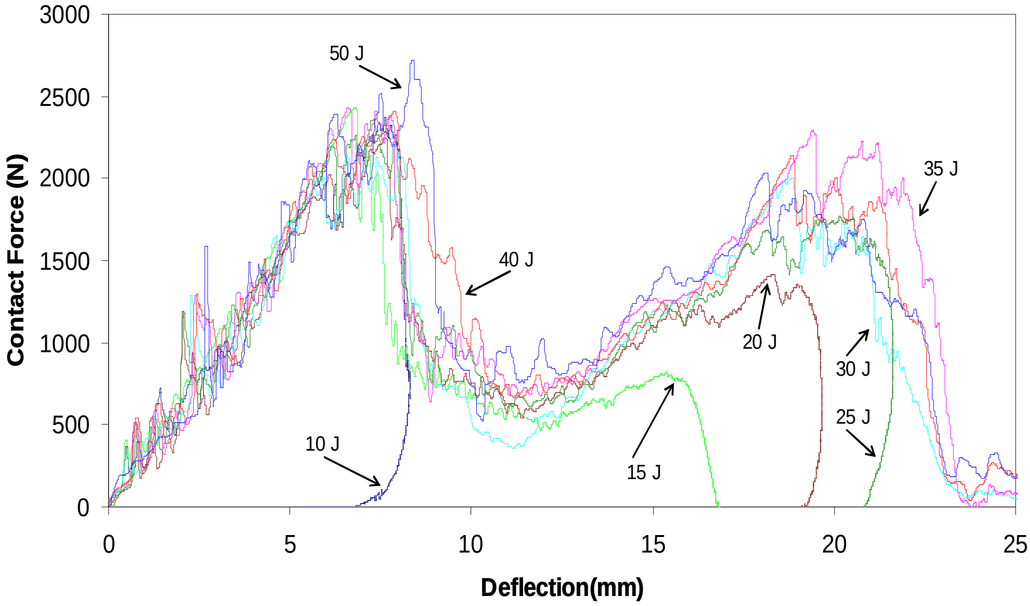


(e)

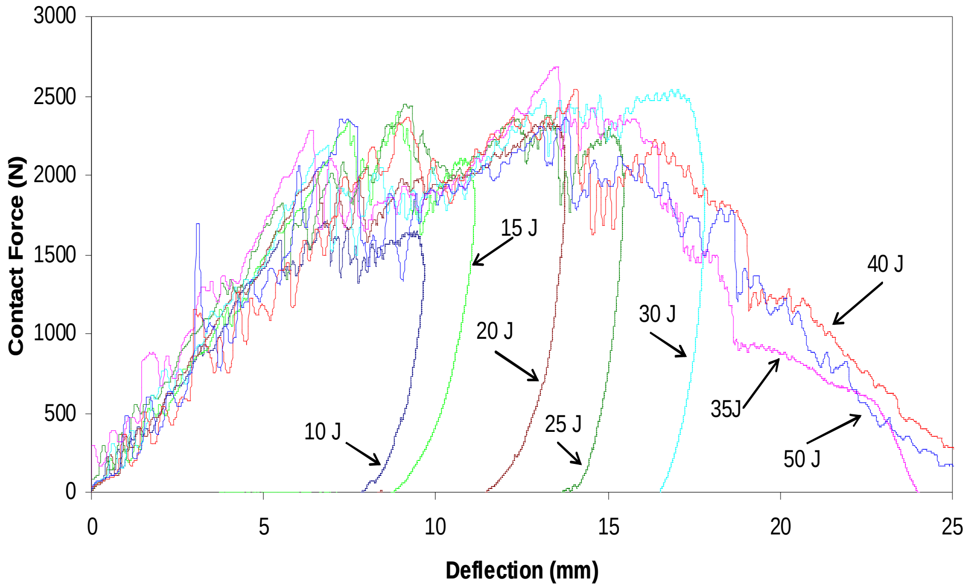
Figure 4.3 Contact force-time diagrams of sandwich composites with core (a) 5mm core, (b) 10 mm core, (c) 5/5 mm core, (d) 15 mm core and (e) 5/5/5 mm core.



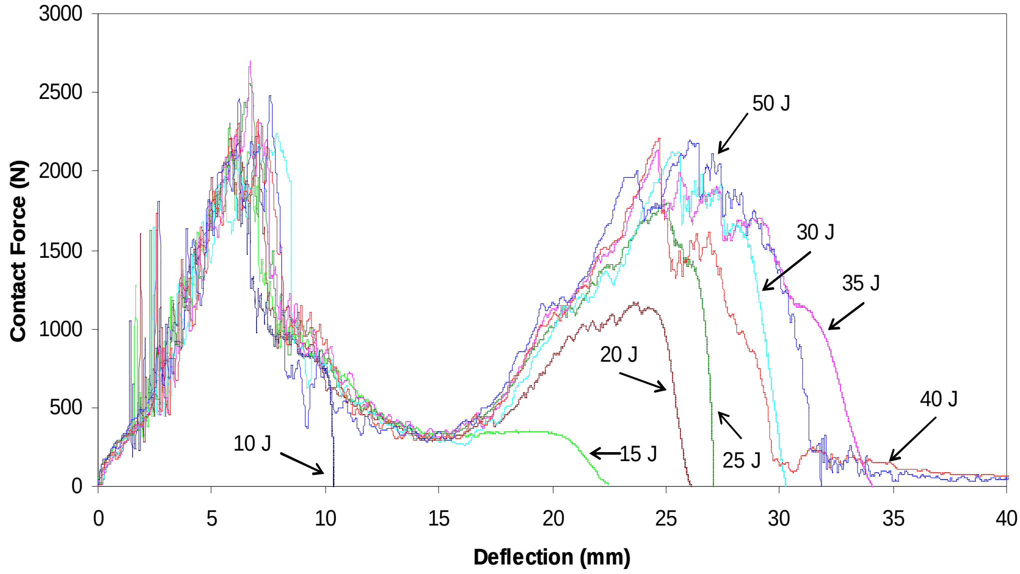
(a)


3000
2500
2000
1500
1000
500
0
Contact Force (N)
0
5
10
15
20
25
Deflection(mm)
50 J
40 J
35 J
10 J
15 J
20 J
30 J
25 J

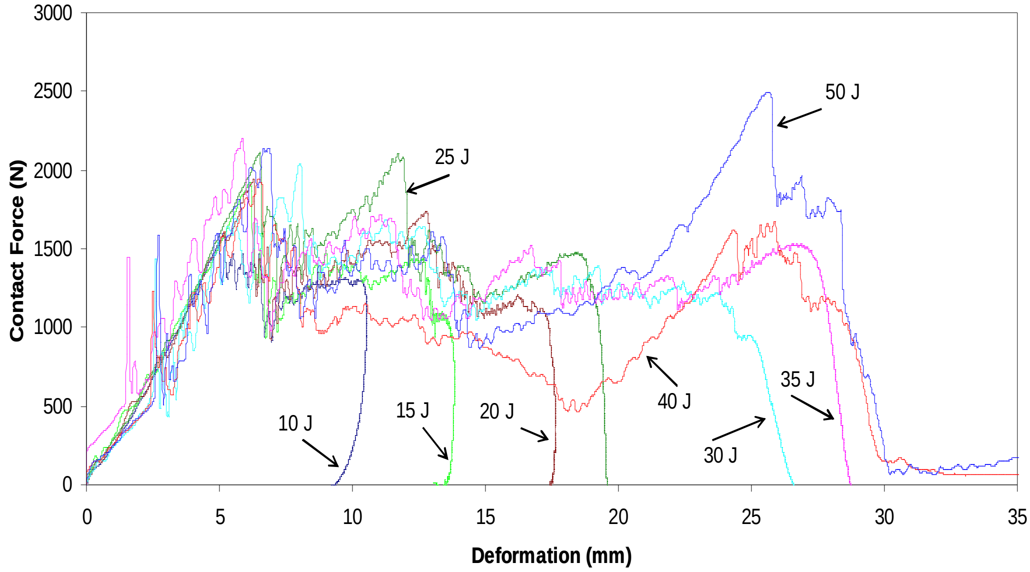
(b)


3000
2500
2000
1500
1000
500
0
Contact Force (N)
0
5
10
15
20
25
Deflection (mm)
15 J
40 J
30 J
20 J
10 J
25 J
35J
50 J

(c)



(d)



(e)

Figure 4.4 Contact force-deflection diagrams of sandwich composites with (a) 5 mm core, (b) 10 mm core, (c) 5/5 mm core, (d) 15 mm core and (e) 5/5/5 mm core.

The results are classified to:

- Effect of the core material thickness on the impact behavior of the sandwich composites.
- Effect of the core material number with variable thickness on the impact behavior of the sandwich composites.
- Effect of the core material number with constant thickness on the impact behavior of the sandwich composites.

4.1.1 Effect of the Core Material Thickness on The Impact Behavior of The Sandwich Composites

4.1.1.1 Experimental Studies

In this study, sandwich composites were manufactured by using vacuum assisted resin infusion molding (VARIM) technique in order to investigate in effect of the core material thickness on the impact behavior by using low velocity impact, experimentally. The results obtained after impacting the specimens of the sandwich composite are shown in the following:

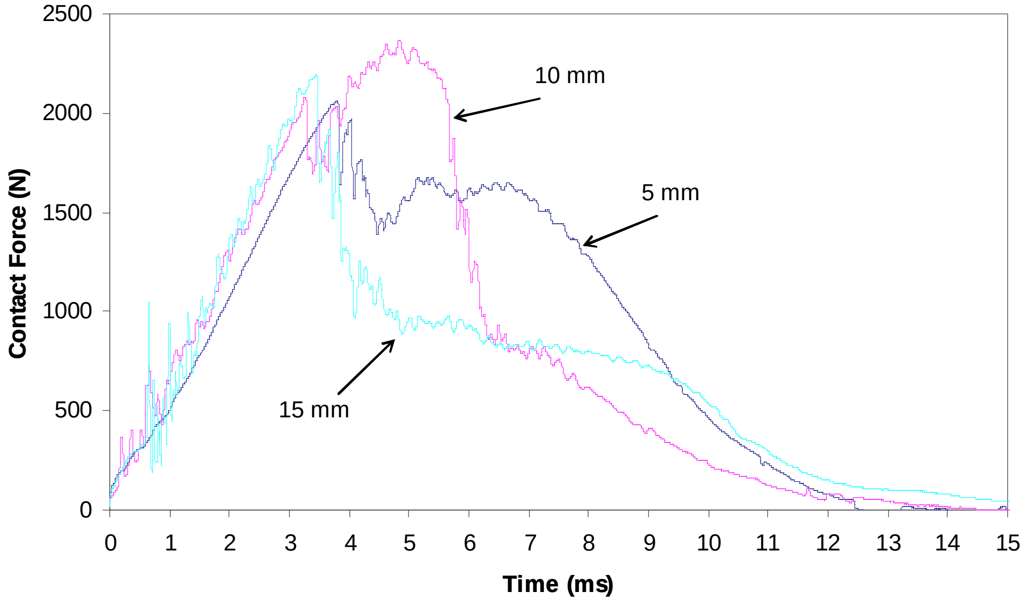
- Contact force-time curves
- Contact force-deflection curves
- Contact force-impact energy curves
- Deflection-impact energy curves
- Time-impact energy curves
- Absorbed energy-impact energy curves

4.1.1.1.1 Contact Force-Time Curves. Figure 4.5 explains Contact force-time of the specimens the sandwich composite which are impacted by 10J, 20J, 35J and 50J energies for three types of thicknesses of one piece core material as 5mm, 10mm and 15mm. The contact force values decrease by increasing the core thickness for each energy level however duration of damage is increasing with increasing the core thickness for each energy level.

We observed that the curves at 10J energy has one peak as shown Figure 4.5.a. which meaning rebounding case for each core material thickness 5mm, 10mm, and 15mm because the impactor is returning after impact the top layer of the specimen and the damages are not noted at bottom layers.

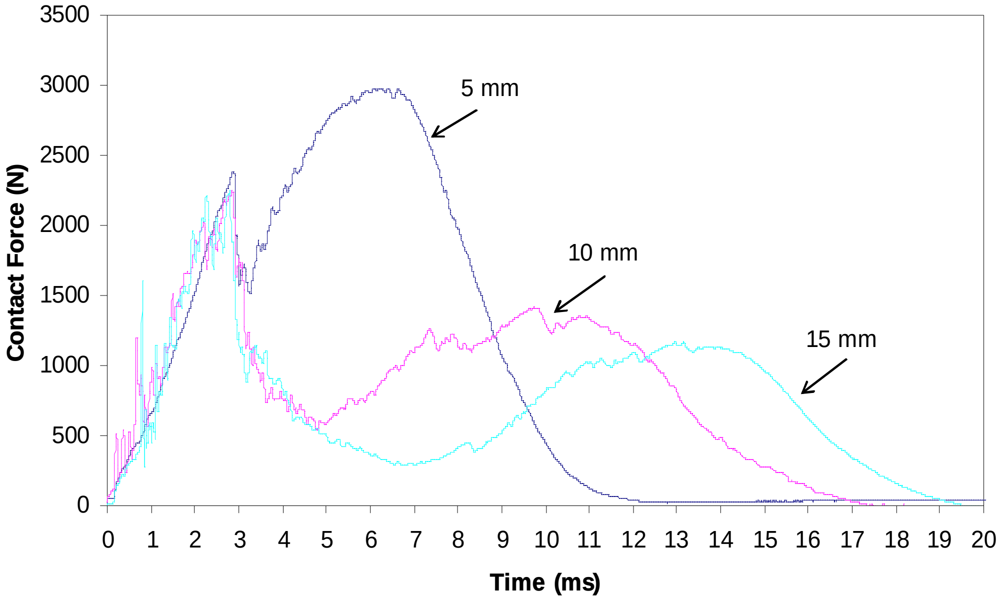
The curves have two peaks at 20J, 35J energies, 5mm core material thickness represents perforation case and the contact force at the second peak increases more than the first peak while 10 mm and 15mm core material thickness the contact force at the first peak increases more than the second peak and they are representing penetration case Figure 4.5.b and Figure 4.5.c. Penetration case occurs when the impactor is penetrating the top layer, the core and the bottom layer respectively and can not return, the damage will be like delamination and fiber cracks in the bottom layer and increases with the rise of impact energy.

And perforation case occurs at 50J energy Figure 4.5.d for all core material thicknesses because the impactor perforates the top and bottom layers and the core so curves have two peaks which indicate damage at top and bottom layers respectively.



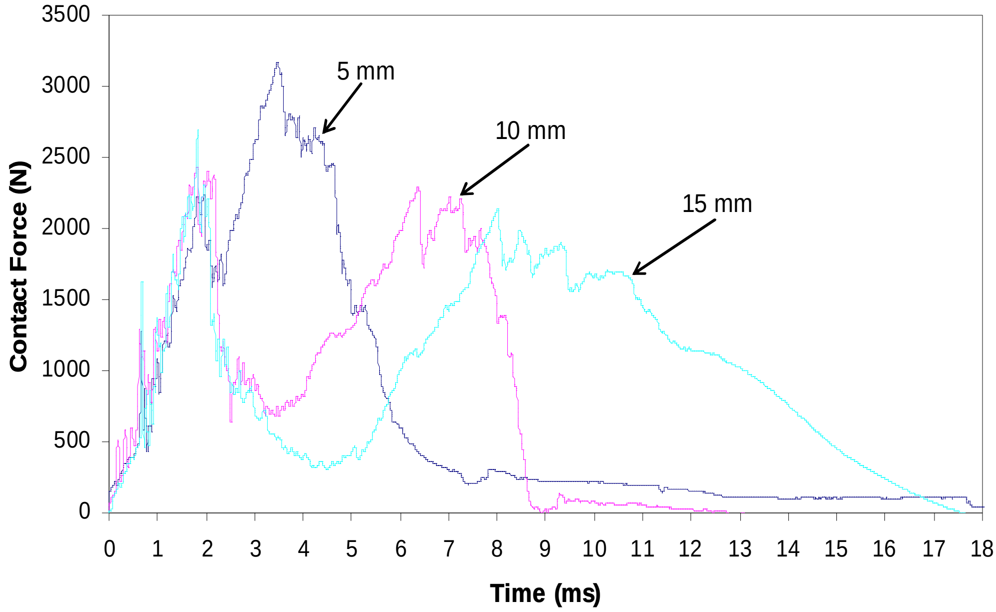
Contact Force (N)
Time (ms)
10 mm
5 mm
15 mm

(a)

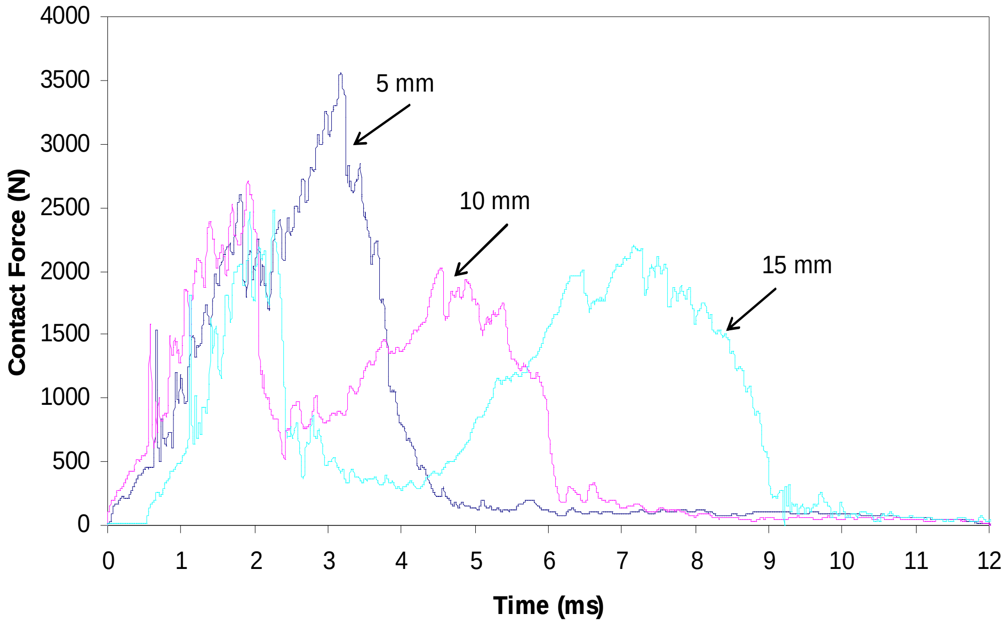


Contact Force (N)
Time (ms)
5 mm
10 mm
15 mm

(b)



(c)



(d)

Figure 4.5 Contact force-time curves of the sandwich composite impacted at (a) 10J, (b) 20J, (c) 35J and (d) 50J.

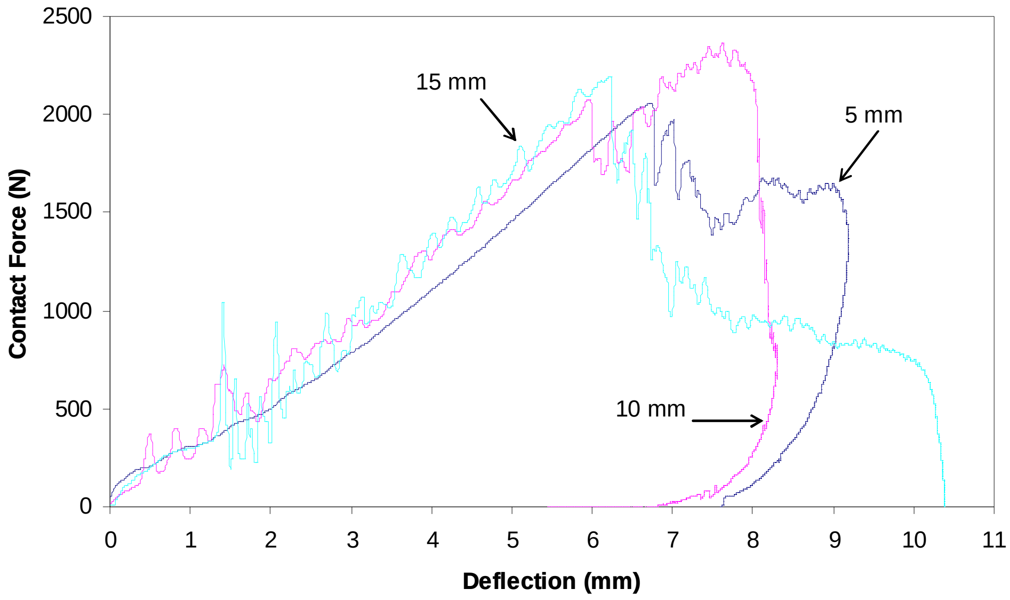
4.1.1.1.2 Contact Force-Deflection Curves. Figure 4.6 explains contact force-deflection curves of the specimens the sandwich composite which impacted at 10J, 20J, 35J, and 50J energies for three types of the core thickness 5mm, 10mm, and 15mm.

The results show that bending stiffness increases by increasing core material thickness at low impact energy in general, the curves have one peak for 10J energy level which means the impactor returns from the top layer after impact: rebounding case occurs for the specimens with cores having 5mm and 10mm thicknesses but for 15mm core material thickness the penetration case occurs and the deflection is more than 5mm and 10mm core material as shown in the Figure 4.6 (a).

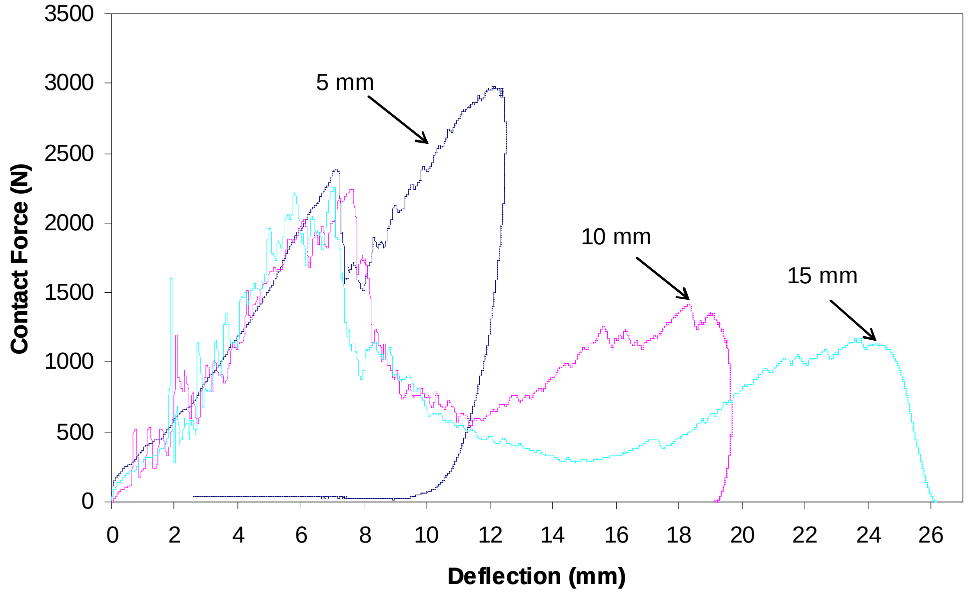
The curves have two peaks for all types of cores, for 5mm core material thickness the curve explains rebounding case, the contact force at second peak increases more than the first peak however for 10mm and 15mm cores curves depict penetration case because the impactor permeates to the top layer, the core and bottom layer respectively and is trapped in the specimens, the contact force in the second peak is less than the first peak and the contact force decreases by increasing the core material thickness but deflection increases by increasing the core material thickness at 20J energy as can be seen in the Figure 4.6 (b).

Contact force-deflection curves are mountain-like shaped for all types of cores and have two peaks because the impactor perforates the specimens. 5mm core material thickness represents the perforation case. The contact force at second peak is bigger than the first peak. On the contrary, for 10mm and 15mm core material thickness represent penetration case, the first and second peaks were nearly similar, the contact force decreases by increasing the core thickness. However, deflection increases by increasing the core thickness at 35J energy in the Figure 4.6 (c).

Figure 4.6 (d) explains perforation case for all core material thicknesses which have two peaks. Curves clearly show that the effect of small core thickness (5mm) is not clear. On the contrary, the effect thicker core material (10 mm and 15 mm) can be seen clear as shown in the Figure 4.6(d). Meanwhile, contact force decreases by increasing the core thickness but deflection increases by increasing the core thickness at 50J.

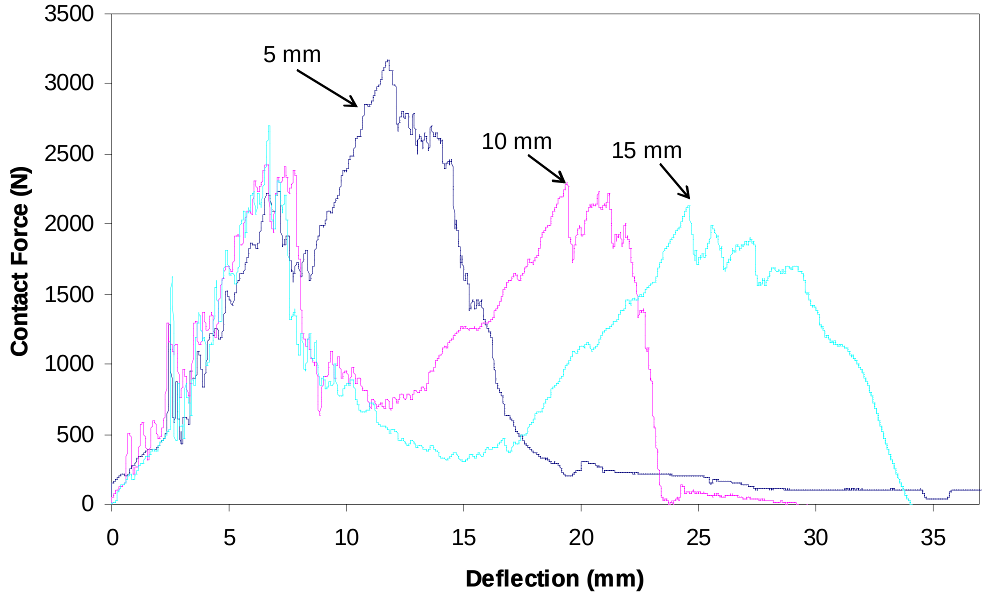


(a)



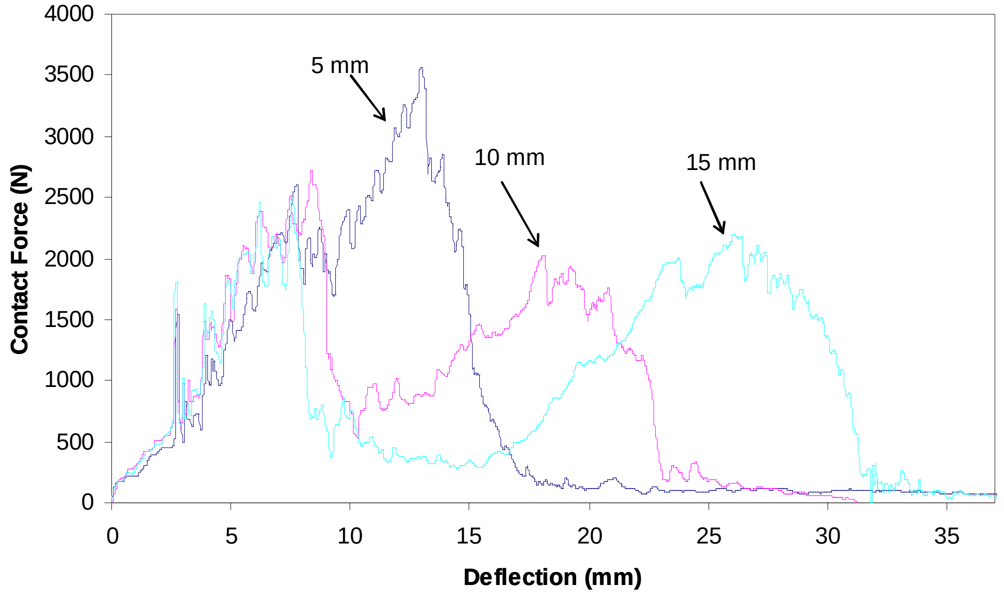
3500
3000
2500
2000
1500
1000
500
0
Contact Force (N)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Deflection (mm)
5 mm
10 mm
15 mm

(b)



3500
3000
2500
2000
1500
1000
500
0
Contact Force (N)
0
5
10
15
20
25
30
35
Deflection (mm)
5 mm
10 mm
15 mm

(c)



(d)

Figure 4.6 Contact force-deflection diagram of the sandwich composite impacted at (a) 10J, (b) 20J, (c) 35J and (d) 50J.

4.1.1.1.3 Contact Force -Impact Energy Curves. Figure 4.7 explains the only peak values of contact force during impact energy, contact force decreases by increasing the core thickness, for the specimens with 5mm core thickness as have small thickness they are more rigid and need bigger contact force than the contact forces for the specimens with 10mm and 15mm cores.

The specimens perform nearly same characteristic with each other for 10mm and 15mm cores; the contact force increases by increasing the impact energy.

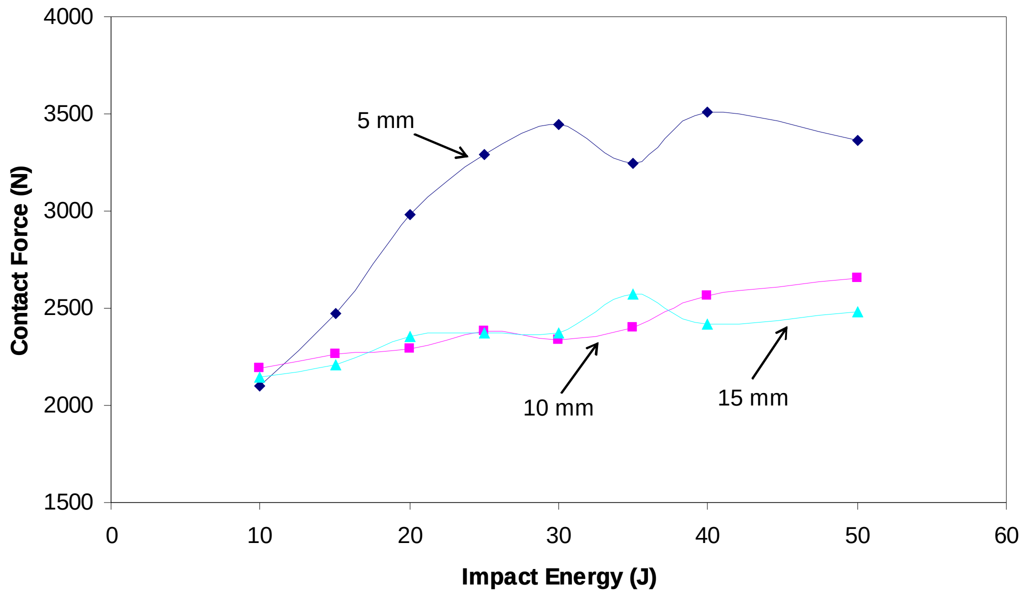


Figure 4.7 Contact force-impact energy diagrams of the sandwich composites with 5mm, 10mm, and 15mm core.

4.1.1.1.4 Deflection-Impact Energy Curves. Figure 4.8 explains maximum deflection-impact energy diagram for three types of the specimens of the sandwich composites which consist from 5mm, 10mm, and 15mm core material thickness. The deflection increases by increasing the core material thickness and the curve of deflection increases by increasing impact energy until 35J impact energy, after that deflection decrease at 40J impact energy for the specimen with 5 mm core and doesn't change until 50J.

The curve of deflection increases by increasing impact energy until 30J impact energy then deflection decrease to 35J energy level and the next deflection increases form 40J to 50J for the specimens with 10mm core while the curve of deflection increases by increasing impact energy until 40J energy after that deflection decrease to 50J energy for the specimens with 15mm core.

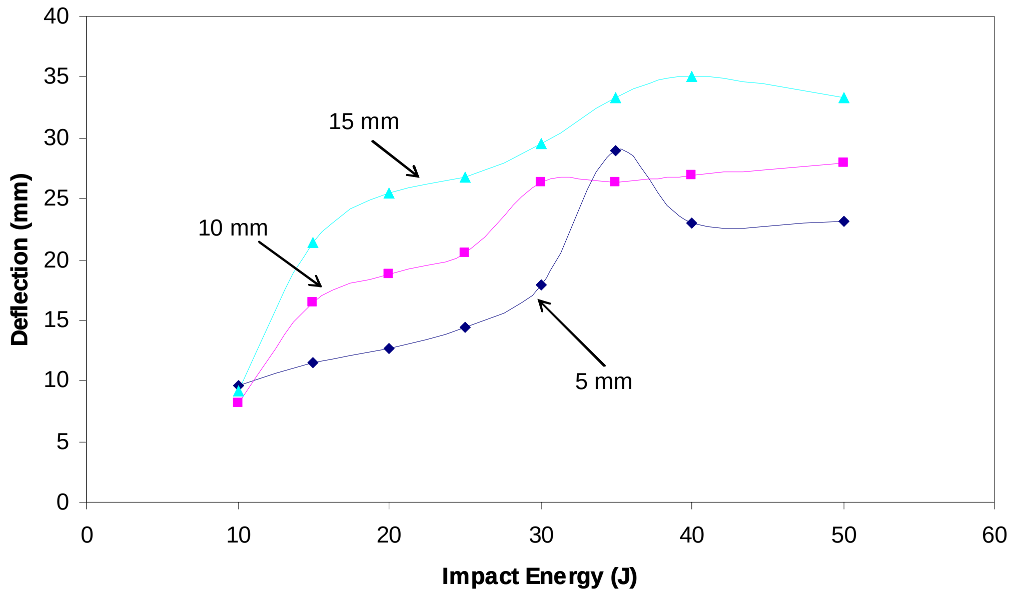


Figure 4.8 Maximum deflection-impact energy diagrams of the sandwich composites with 5mm, 10mm, and 15mm core.

4.1.1.1.5 Time-Impact Energy Curves. Time-impact energy diagram is given in Figure 4.9. The time increases by increasing the core material thickness however decreases by degrees with increasing impact energy for all specimens of the sandwich composite which consist of 5mm, 10mm, and 15mm core material thickness. The curves have one peak for the specimens with 5mm and 10mm cores while for the specimens with 15mm core the curve has two peaks.

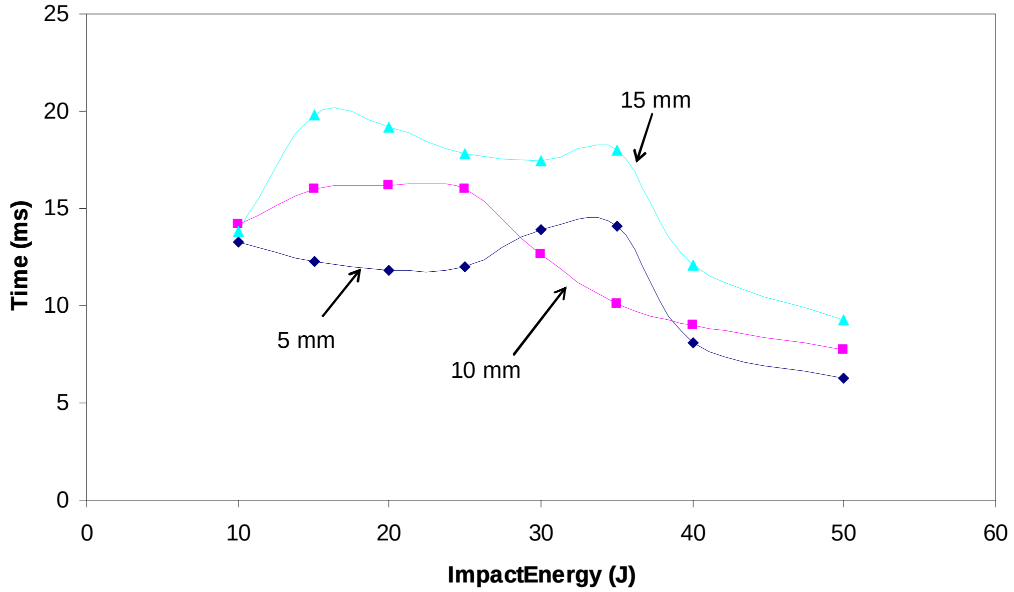


Figure 4.9 Time-impact energy diagram of the sandwich composite with 5mm, 10mm, and 15mm core.

4.1.1.1.6 Absorbed energy-Impact Energy Curves. Energy profile diagram represents absorbed energy versus impact energy as shown in the Figure 4.10. For three types of the specimens the sandwich composite, the energy profile diagram explains difference between three types of the core material thicknesses which are 5mm, 10mm, and 15mm.

The penetration threshold starts at 25J for 5mm and 15mm cores while penetration threshold occurs at 20J for 10mm core specimens. The perforation threshold occurs at 30J energy for 5mm core material thickness, at 25J energy for 10mm core however, at 35J energy for 15mm core material thickness.

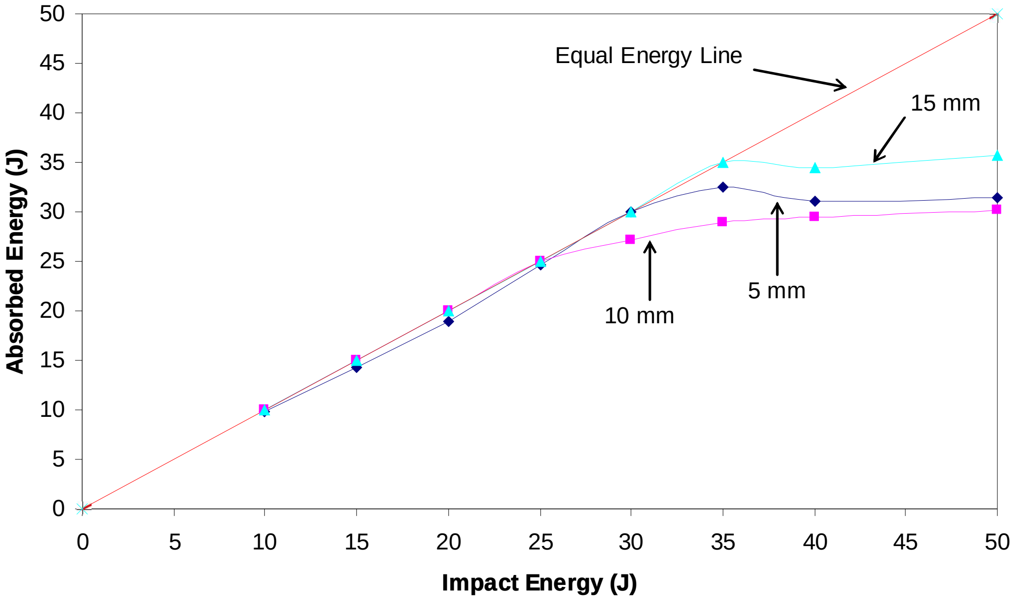


Figure 4.10 Absorbed energy-impact energy diagram of the sandwich composite with 5mm, 10mm, and 15mm core.

4.1.1.2 Numerical Study

4.1.1.2.1 Introduction. In the numerical study, the traditional sandwich composite which consists of core PVC foam with 5mm thickness between top and bottom layers is modeled and analyzed for 10J impact energy by using LS-DYNA. Stacking sequences of sandwich composite is [0º/90º/0º/PVC foam/0º/90º/0º]. Contact force – time and contact force–deflection diagrams were plotted and compared with that obtained from the experiment.

4.1.1.2.2 Modeling of Sandwich Composite. Modeling of the traditional sandwich composite with impactor is shown in the Figure 4.11. The Mat Enhanced Composite Damage (MAT_054-055) was used to model unidirectional E-glass 0º/90º fabric as a shell structure. Mat Low Density Foam (MAT_057) was used to model the core however the impactor was modeled as a rigid body (sphere) by using Mat Rigid MAT_020.

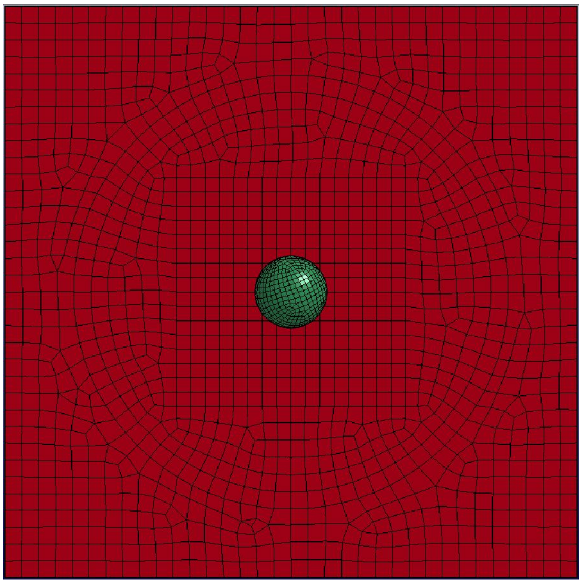
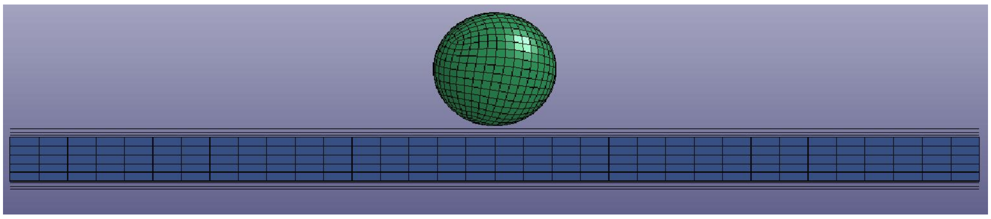


Figure 4.11 Traditional sandwiches composite with impactor.

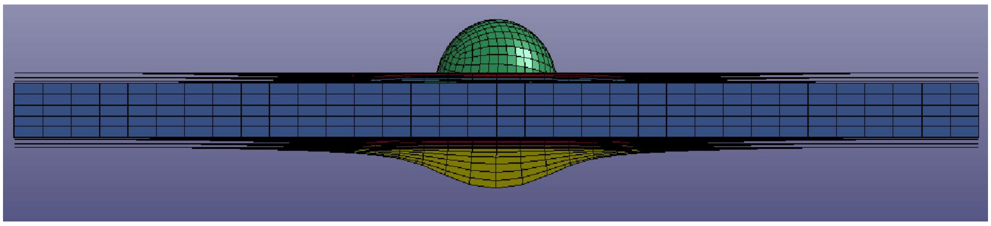
Table 4.1 The sandwich composites and impactor properties

	core	0º direction with Epoxy	90º direction Epoxy	impactor
Density (kg/m³)	60	2300	----	7860
E1 MPa	42	2860	10760	200000
G12 MPa	21.5	7390	4434	76923
υ_{12}	0.16	0.26	0.156	0.3

Figure 4.12 shows numerical model of the traditional sandwich composite before and after impact.



(a)

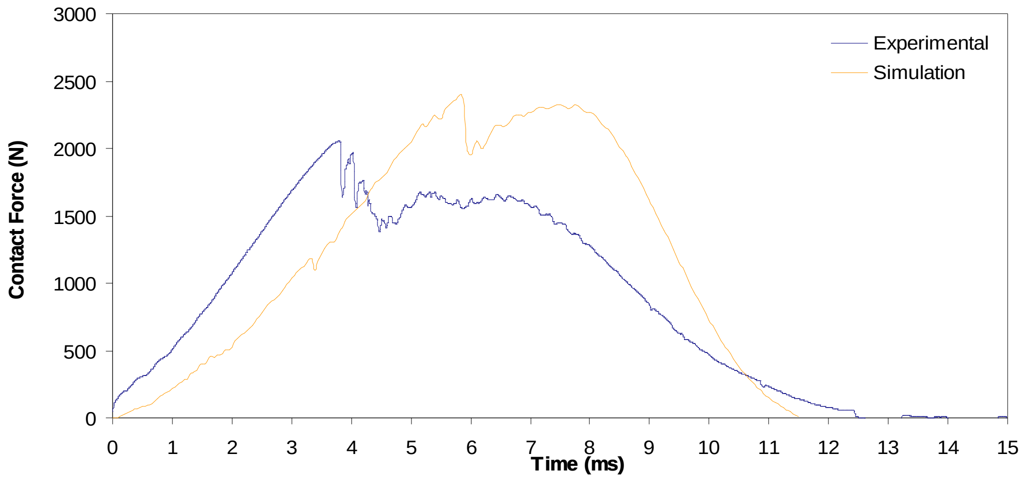


(b)

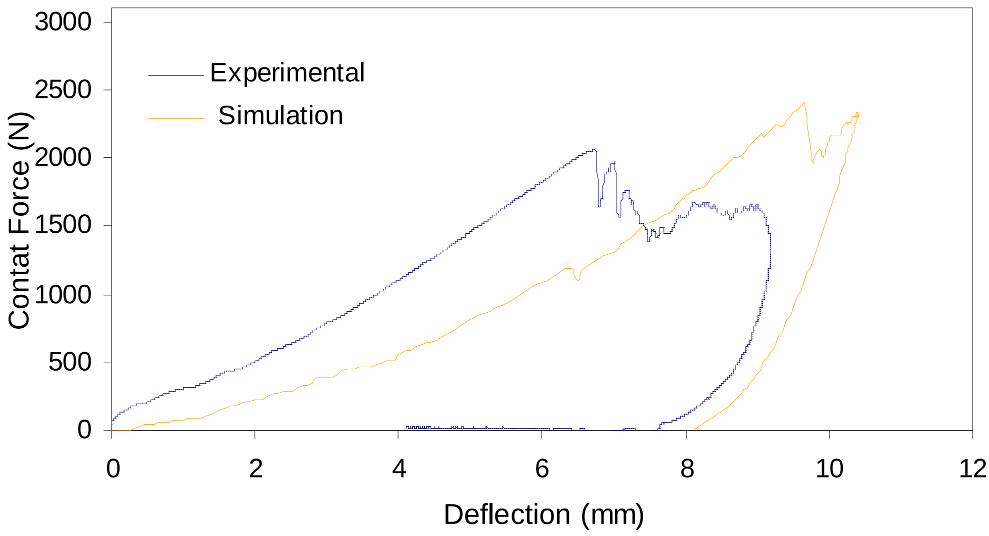
Figure 4.12 Traditional sandwiches composite (a) before impact (b) after impact

4.1.1.3 Comparison of Experimental and Numerical Results

The contact force versus time and contact force versus deflection are shown in the Figure 4.13. Numerical results were compared with that obtained from experimental study. It is seen from the curves that, there is good agreement between numerical study and experimental study. There are two peaks, which is meaning penetration threshold for experimental and numerical studies.



(a)



(b)

Figure 4.13 Experimental and Numerical results **(**a) Contact force-time curves (b) Contact force-deflection curves.

4.1.2 Effect of The Core Material Number with Variable Thickness on The Impact Behavior of The Sandwich Composites

In this part, we are going to discuss impact behavior for the sandwich composites which affected by the core material number, by using 5mm, 5/5mm, and 5/5/5mm cores material between six layers including internal sheet, the results are obtained after impacted the specimens of the sandwich composite are shown in the following:

- Contact force-time curves
- Contact force-deflection curves
- Contact force-impact energy curves
- Deflection-impact energy curves
- Time-impact energy curves
- Absorbed energy-impact energy curves

4.1.2.1 Contact Force-Time Curves

The specimens of the sandwich composites in this study were manufactured by bonding same PVC foam between top and bottom layers including internal sheet in order to obtain two-core and three-core sandwich composites, and PVC foam between top and bottom layers to obtain conventional sandwich composites, the results are obvious after impact by 10J, 20J, 35J, and 50J energies, contact force values decrease by increasing the core number for each energy level. However, the time values are increasing by increasing the core number. As shown in Figure 4.14.

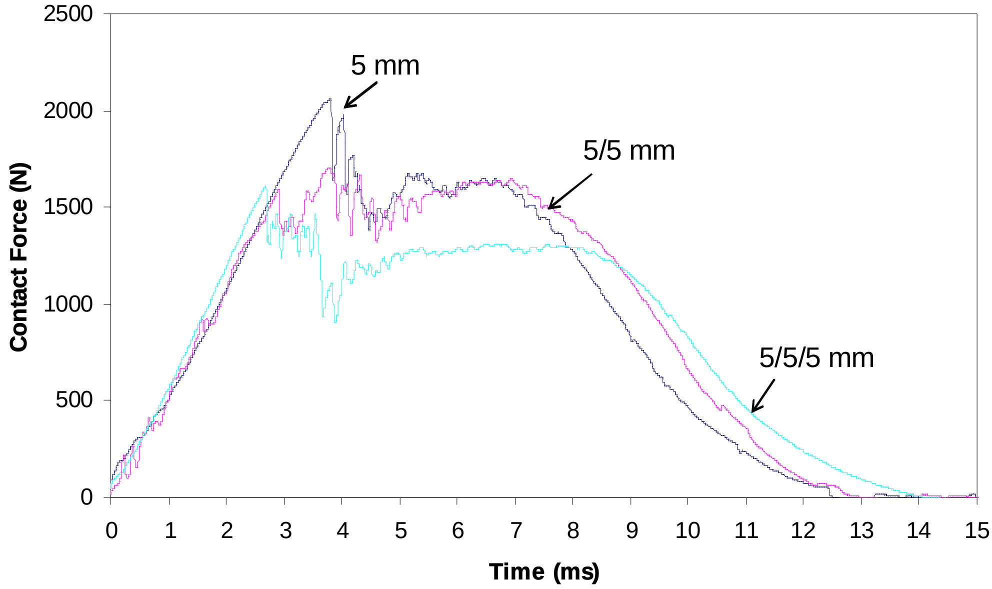
The Figure 4.14(a) explains the curves for 5mm, 5/5mm, and 5/5/5mm which have one peak after impact samples at 10J energy. The impactor returns from the test sample after impact at top layer due to extravagant energy, which retains in the impactor and it means rebounding case. The damage is observed only at top layer as delamination and matrix crack.

At 20J energy as can be seen from the Figure 4.14(b), the damage occurs at top and bottom layers so the curve has two peaks and the damage is observed as delamination, matrix cracks and fiber breakage for the specimen with one core of 5mm. The contact force and deflection at the second peak increase more than the first peak, but for the specimen with two-core (5/5mm) and three-core (5/5/5mm) the delamination and matrix cracks occur only at top layer.

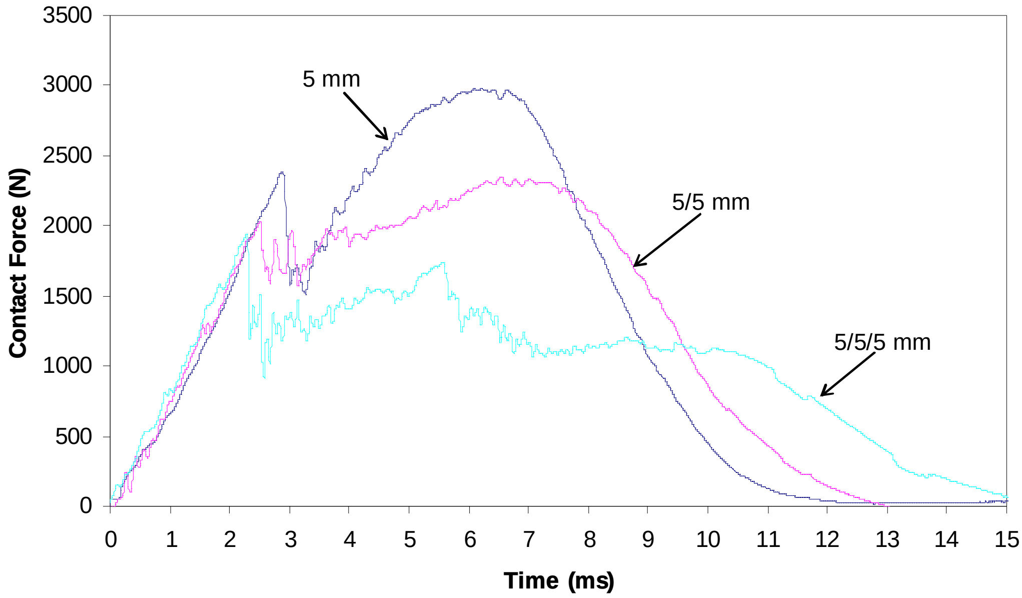
The Figure 4.14(c) explains the difference between the core number, for one-core specimen the curve has two peaks and represents perforation case which occurs at 35J energy, and for the specimen with two-core, the curve has three peaks because two-core have one-internal sheet and represents penetration case, while for three-core, the curve has four peaks because three-core have two-internal sheet and the damage occurs at top layer, two-internal sheet, bottom layer respectively, and the curve represents penetration case. The impactor is trapped in the specimen regardless of the core numbers.

The curves in Figure 4.14(d) show for 50J energy, with one-core specimen the curve has two peaks because the damage is in the top and bottom layers as delamination, matrix cracks and fiber crack, which represents perforation case.

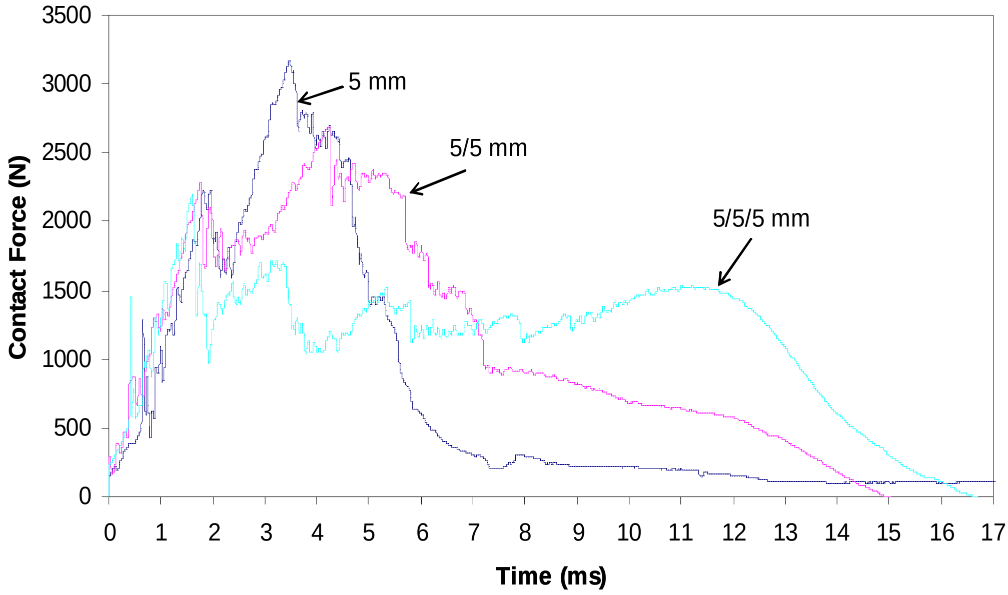
The curve of two-core specimen represents penetration case and has damage in top layer, internal sheet, bottom layer respectively, as delamination, matrix cracks and fiber breakage. While the curve of specimens with three-core represents perforation case and has four peaks because of top and bottom layers and three-core have two-internal sheet. The contact forces of three-core and two-core specimen are less than one-core specimen and the time for three-core is bigger than one-core and two-core.


2500
2000
1500
1000
500
0
Contact Force (N)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (ms)
5 mm
5/5 mm
5/5/5 mm

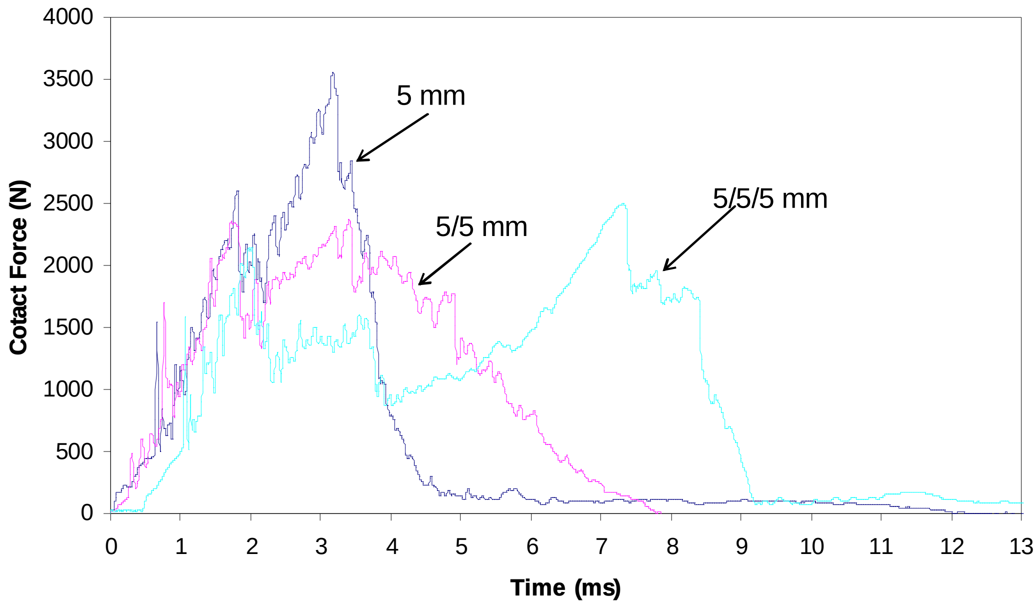
(a)


3500
3000
2500
2000
1500
1000
500
0
Contact Force (N)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (ms)
5 mm
5/5 mm
5/5/5 mm

(b)



(c)



(d)

Figure 4.14 Contact force-time diagram of the sandwich composites impacted at (a) 10J, (b) 20J, (c) 35J and (d) 50J.

4.1.2.2 Contact Force-Deflection Curves

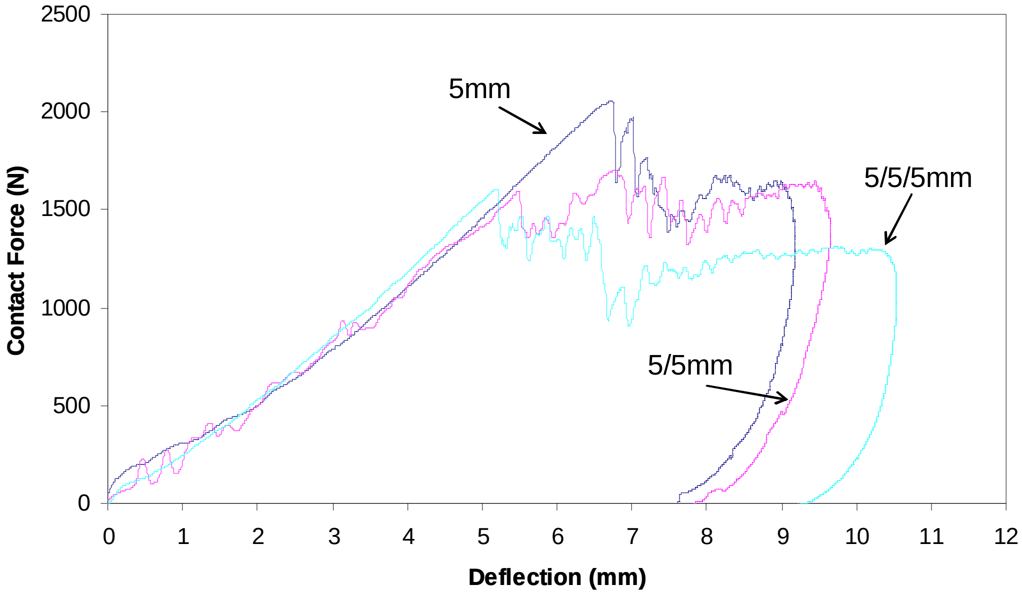
As seen from the Figure 4.15, Contact force-deflection curves are given for specimens of sandwich composite which consist of closed curve and open curve. Closed curve contains ascending section representing loading and descending section represents unloading, if the descending section is be zero due to friction between specimens and impactor it means open curve (perforation case), three types of the cores with 5mm, 5/5mm, and 5/5/5mm cores were prepared for impacting at 10J, 20J, 35J, and 50J energies. Contact force values decrease by increasing the core number while deflection increases by increasing the core number in each energy level.

The bending stiffness increases by increasing core material thickness in the conventional sandwich composites by using smaller energies (10 J) that is, as noted earlier, however can not say that for multi cores, the Figure 4.15(a) explains rebounding case for three types of the core and each curve has one peak because the impactor returns from the top layer after impact at 10Jenergy.

The curves have two peaks for two types of the core number; one-core 5mm and two-core 5/5mm while for three-core, the curve has three peaks. Figure 4.15(b) shows samples impacted by dropping weight impact testing at 20J energy. Contact force in the second peak increases more than the first peak and the impactor returns after impact for specimen with one-core and two-core which means rebounding case, while penetration case occurs for three-core. The impactor permeates to top layer, the first core, and internal sheet, respectively and is trapped in the specimens. Contact force decreases by increasing the core number however deflection increases by increasing the core number, the contact force in the second peak less than the first peak.

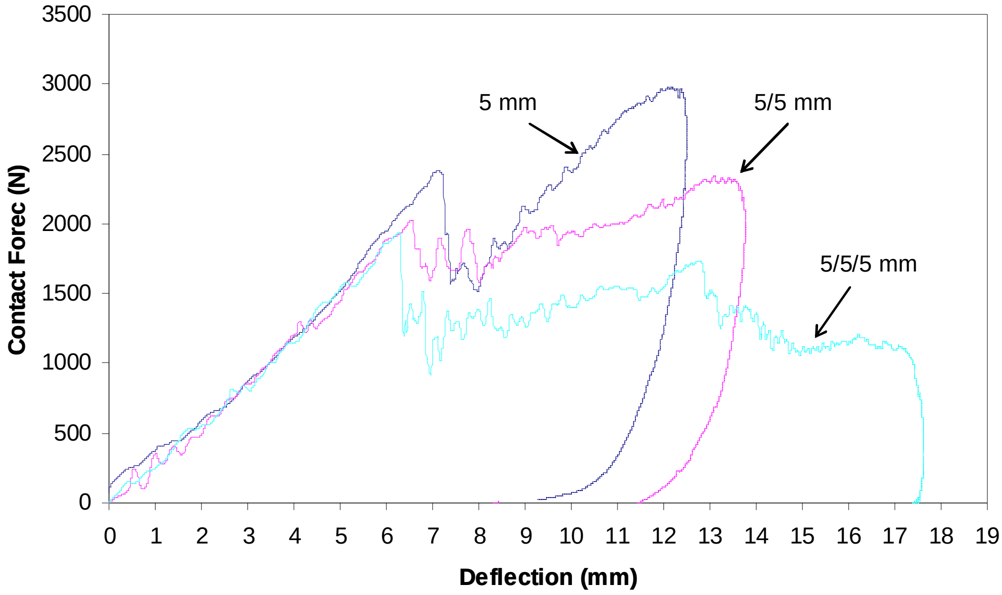
The Figure 4.15(c) explains perforation case which occurs for one-core at 35J energy. The damages such as delamination, matrix crack, and fiber crack occur at top and bottom layers. Contact force in the second peak increases more than the first peak. Penetration threshold occurs for two-core and three-core specimen, two-core specimen consists of three peaks, while three-core consists of four peaks and the damage is as delamination, matrix crack, starting at top layer, followed by first core, internal sheet, second core, internal sheet, third core, bottom layer, respectively.

The Figure 4.15(d) explains penetration case which occurs for two-core, this means that impactor does not rebound from the specimen; however perforation case occurs for one-core and three-core at 50J energy. The curve has two peaks for one-core, while curve has three peaks for two-core and contains four peaks for three-core, due to stiffness of bottom layer during impact test which increases by increasing the core thickness or the core number for (20J, 35J and 50J) higher energies, so the second peak can be bigger than first peak. The damages occur initiating from top layer, followed by first core, internal sheet, second core, internal sheet, and third core, bottom layer respectively in the modes of delamination, matrix crack and fiber breakage.



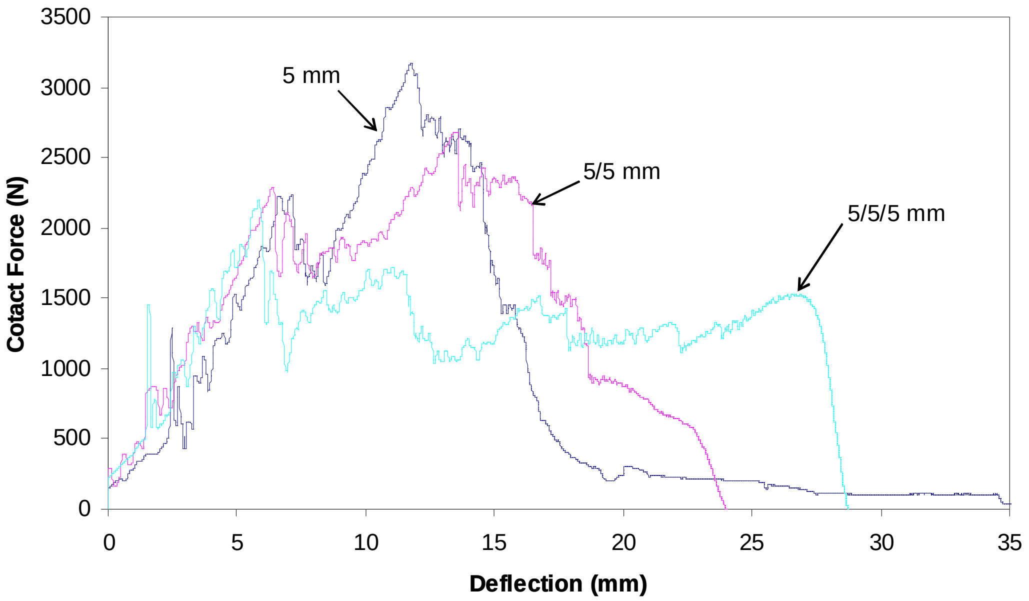
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Contact Force (N)
Deflection (mm)
5mm
5/5/5mm
5/5mm

(a)

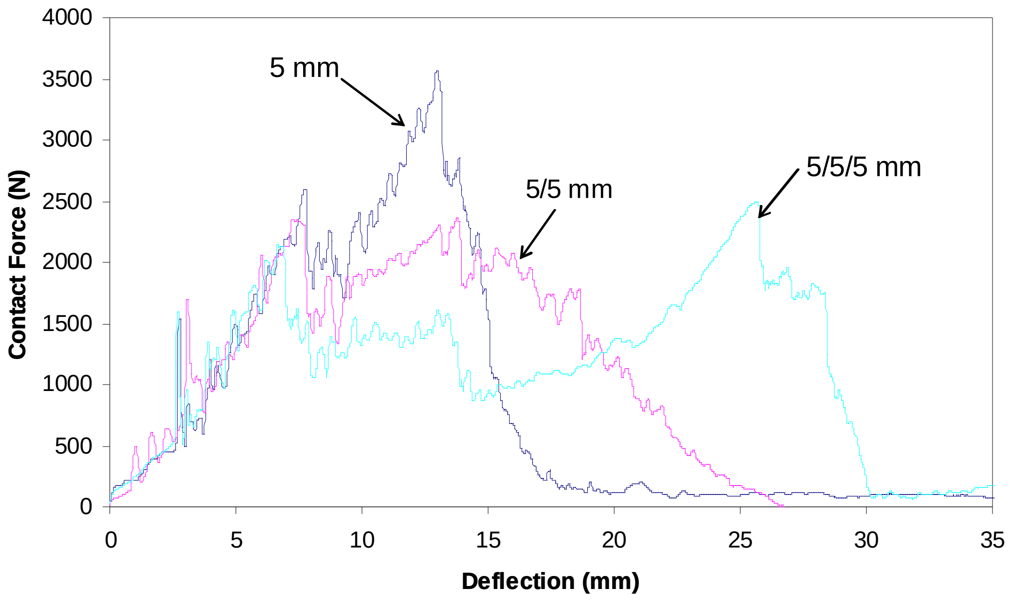


3500
3000
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Contact Forec (N)
Deflection (mm)
5 mm
5/5 mm
5/5/5 mm

(b)



(c)



(d)

Figure 4.15 Contact force-deflection diagram of the sandwich composite impacted at (a) 10J, (b) 20J, (c) 35J and (d) 50J.

4.1.2.3 Contact Force -Impact Energy Curves

From the Figure 4.16 Contact force-impact energy diagram for three types of the specimens can be seen. Which consist of 5mm, 5/5mm, and 5/5/5mm core material numbers.

The contact force increases with increasing the impact energy up to 30J because after 30J energy the perforation case occurs for one-core however the contact force increases by increasing the impact energy up to 35J energy because after 35J energy the perforation case occurs for two-core and three-core specimen. Contact force decreases by increasing core numbers, the curves show the only peak values of contact force during impact energy, for one-core 5mm, the specimens have small thickness so are more rigid and need contact force bigger than two-core 5/5mm and three-core 5/5/5mm specimen.

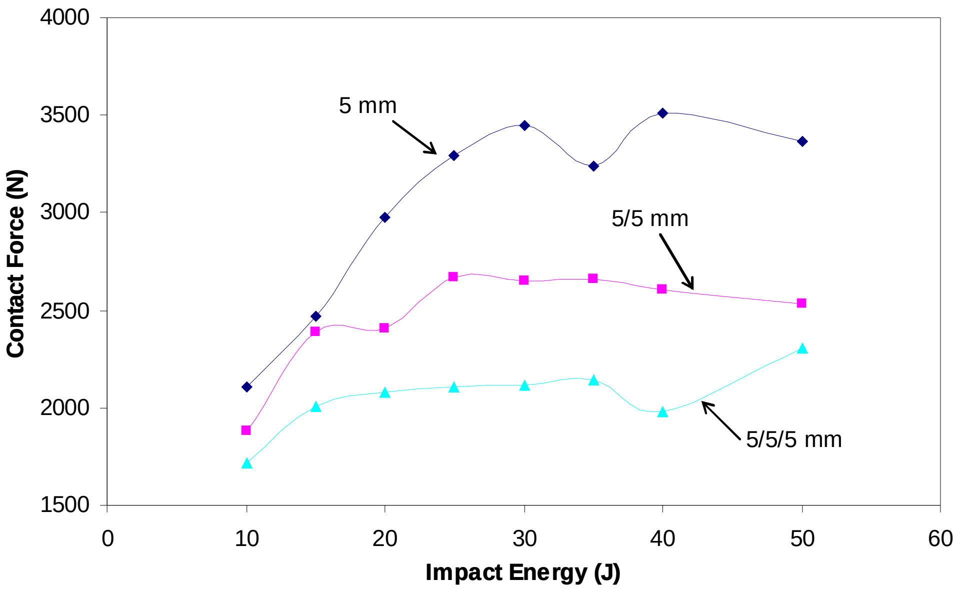


Figure 4.16 Contact force-impact energy diagrams of the sandwich composites with 5mm, 5/5mm, and 5/5/5mm core.

4.1.2.4 Deflection-Impact Energy Curves

The maximum deflection-impact energy diagram for three types of specimens which consist of 5mm, 5/5mm, and 5/5/5mm core is given in the Figure 4.17. The curve has one peak for one-core while the curve has two peaks for two-core and the curve has three peaks for three-core specimen.

The maximum deflection curve increases by increasing impact energy until 35J energy, after that deflection decrease at 40J energy and increases at 50J energy for one-core, however the maximum deflection curve increases by increasing impact energy until 40J energy and then deflection decreases by increasing the impact energy form 40J to 50J due to the failure in the core due to shear and compressive loads for two-core and three-core specimen.

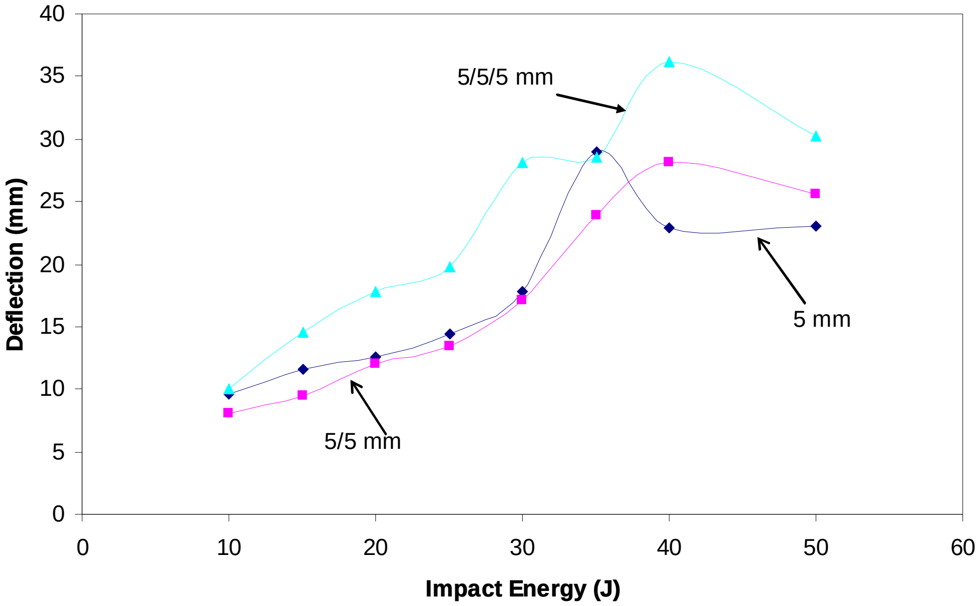


Figure 4.17 Maximum deflection-impact energy diagrams of the sandwich composites with 5mm, 5/5mm, and 5/5/5mm core.

4.1.2.5 Time-Impact Energy Curves

Time-impact energy diagram for three types of the specimens which consist of one-core, two-core and three-core is given in the Figure 4.18.

The time decreases by increasing impact energy until 25J energy, after that increases between 30J and 35J energy and due to perforation the time decreases by increasing impact energy and the curve has one peak for one-core while the curves have two peaks for two and three cores specimen. The time increases by increasing impact energy until 35J energy after that decreases due to perforation for two cores however the time increases by increasing impact energy until 30J energy after that decreases for three-core specimen.

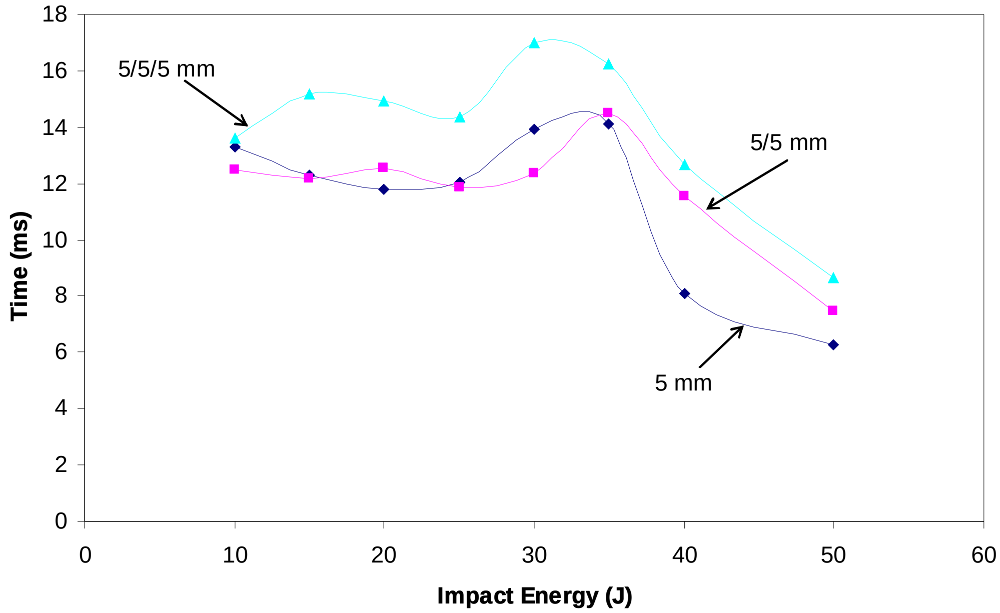


Figure 4.18 Contact time-impact energy diagram of the sandwich composites with one-core, two-core and three-core.

4.1.2.6 Absorbed Energy-Impact Energy Curves

As can be seen from the Figure 4.19 absorbed energy-impact energy diagram for three types of the specimens consist of one-core, two-core and three-core are given.

The energy profile diagram explains the differences between one, two and three cores specimen. The penetration threshold of one-core (0/90/0/core/0/90/0) starts approximately at 25J however penetration threshold of (0/90/core/0/0/core/90/0) and (0/90/core/0/core/0/core/90/0) occur at 30J for two-core and three-core, respectively. The perforation threshold occurs at 30J energy for one-core; while the perforation threshold occurs at 35J energy for two and three cores. The absorbed energy values almost do not change after perforation case for the two-core and three-core as shown in the Figure 4.19.

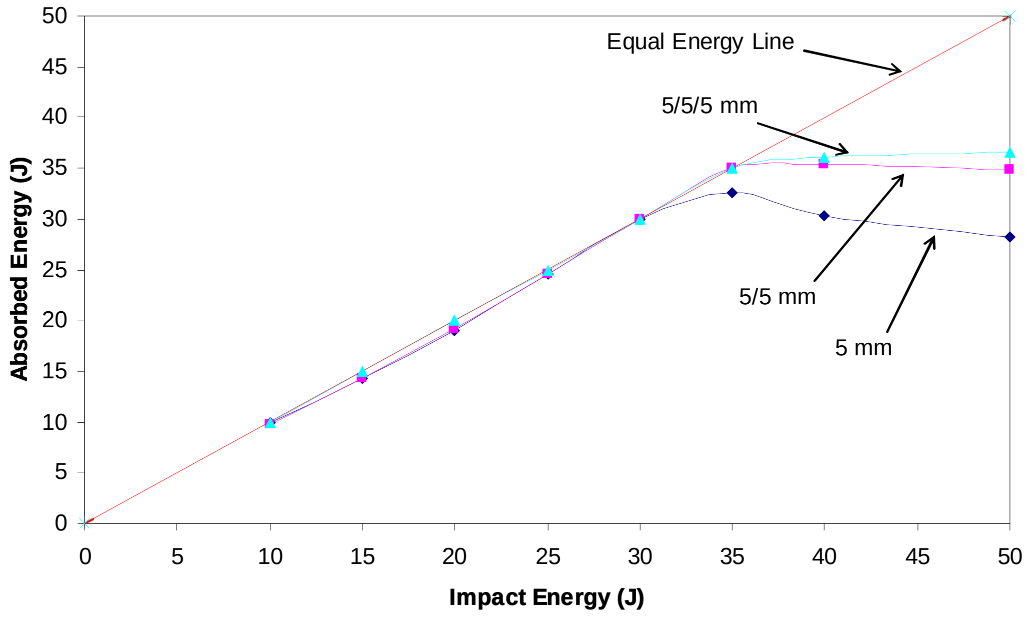


Figure 4.19 Absorbed energy-impact energy diagram of the sandwich composites with one-core, two-core and three-core.

4.1.3 Effect of The Core Material Number with Constant Thickness on The Impact Behavior of The Sandwich Composites

In this part, we will compare between two types of core material with constant thickness in effect on impact behavior of the sandwich composites by using:

- the core material thickness 10mm and 5/5mm
- the core material thickness 15mm and 5/5/5mm

4.1.3.1 The Core Material Thickness 10mm and 5/5mm

The comparison between conventionally designed and two-core with internal sheet inserted into the core sandwich composites with constant thickness in effect on low velocity impact (LVI) response is investigated; two types of synthetic sandwich composites having six layers are manufactured by using vacuum assisted resin infusion molding (VARIM). E-glass fabric as reinforcement are chosen and PVC foam core C.71.55 with 10mm and 5/5 mm thickness are used in the conventionally designed and two-core sandwich composites, respectively.

Stacking sequences of sandwich composites were [0º/90º/0º/PVC foam/0º/90º/0º] and [0º/90º/PVC foam/0º/0º/PVC foam/90º/0º]. Specimens prepared with dimensions of 100x100 mm were subjected to low velocity impact (LVI). Impactor height is various to give a level of impact energy from 10J to 50J with constant impactor mass of 5 kg. The results are obtained shown in the following.

- Contact force-impact energy curves
- Deflection-impact energy curves
- Time-impact energy curves
- Absorbed energy-impact energy curves

4.1.3.1.1 Contact Force -Impact Energy Curves. It can be seen from the Figure 4.20. Contact force-impact energy diagram explains the comparison between two types of the specimens which consist of 10mm and 5/5mm core material.

Contact force increases by increasing the core number, the curves show only peak values of contact force during impact energy, the specimens have same thickness for 10mm and 5/5mm but contact force is different.

The contact force increases by increasing the impact energy to 35J energy because of the perforation case which occurs for two-core specimen however the contact force increases by increasing the impact energy for one-core and the perforation case occurs at 25J energy for one-core. The contact force in two-core is higher than one-core up until 40J energy.

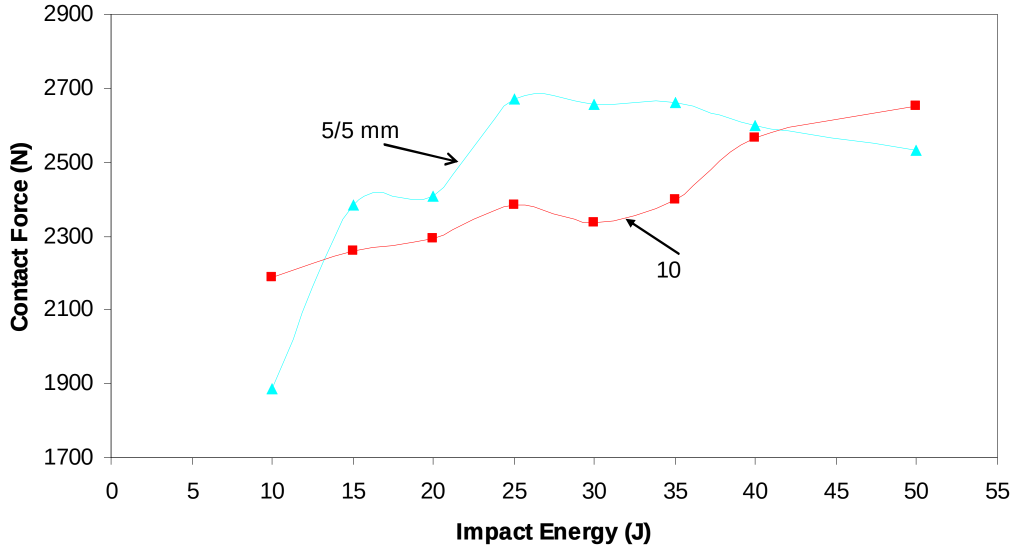


Figure 4.20 Contact force-impact energy diagram of the sandwich composites with one-core and two-core.

4.1.3.1.2 Deflection-Impact Energy Curves. The deflection-impact energy diagram shows the comparison between traditional and multi core of the sandwich composite which consist of 10mm, and 5/5mm core material as shown in the Figure 4.21.

The curve of deflection increases by increasing impact energy until 40J energy after that deflection decrease for two-core while deflection increases by increasing impact energy for one-core.

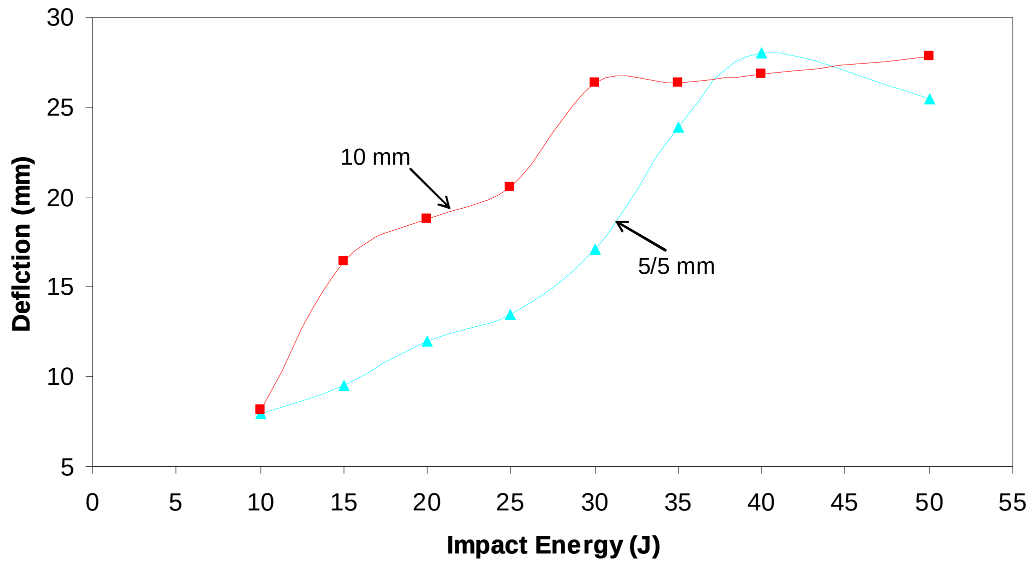


Figure 4.21 Deflection-impact energy diagrams of the sandwich composites with one and two cores.

4.1.3.1.3 Time-Impact Energy Curves. Time with impact energy can be seen in Figure 4.22. Comparison between two types of the specimen which consist of same thickness 10mm, and 5/5mm core material are done.

The time has two peaks in multi core sandwich composites however one peak exists for conventionally designed sandwich composites and the time decreases by increasing impact energy until 30J energy after that increases to 35J energy and because of perforation threshold the time decreases by increasing impact energy in multi cores however the time increases by increasing impact energy until 25J energy after that decreases because of perforation threshold in conventionally designed of sandwich composites.

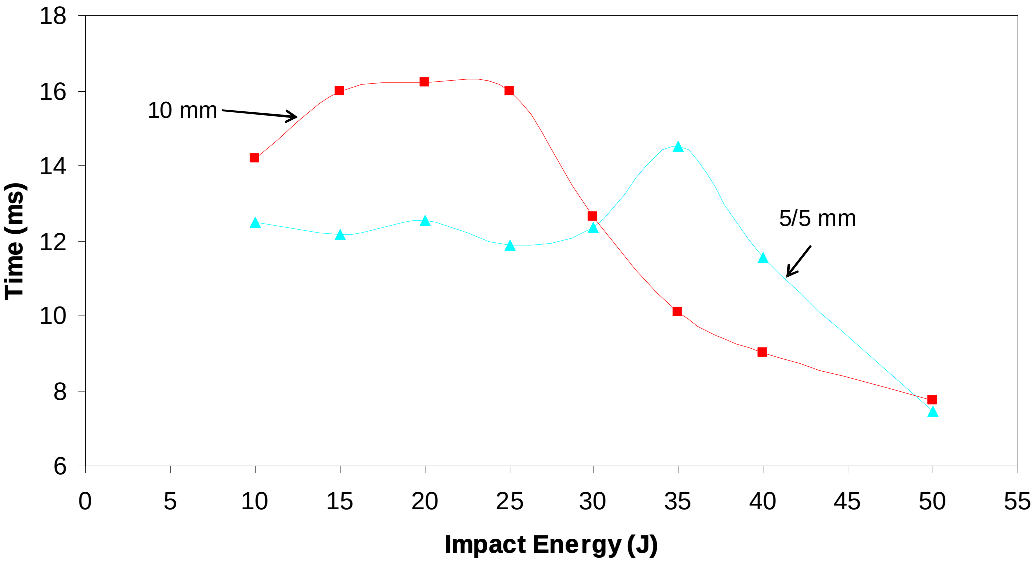


Figure 4.22 Time-impact energy diagram of the sandwich composites with one and two cores.

*4.1.3.1.4 Absorbed Energy-Impact Energy Curves***.** The Figure 4.23 explains absorbed energy-impact energy diagram for two types of the specimens which consist of same thickness but one piece10mm and two pieces 5/5mm cores material.

Absorbed energy is more significantly influenced by core number; the energy profile diagram explains the differences between one-core and two-core. The penetration case starts at 30J energy for two-core while penetration case occurs at 20J energy for one-core. The perforation threshold occurs at 25J energy for one-core however the perforation threshold occurs at 35J energy for two-core specimen. It can be seen from Figure 4.23. Energy absorption capacity for multi core sandwich composite is better than traditional sandwich composite and with increasing in the impact energy absorbed energy almost doesn't change after perforation case occurs for two-core.

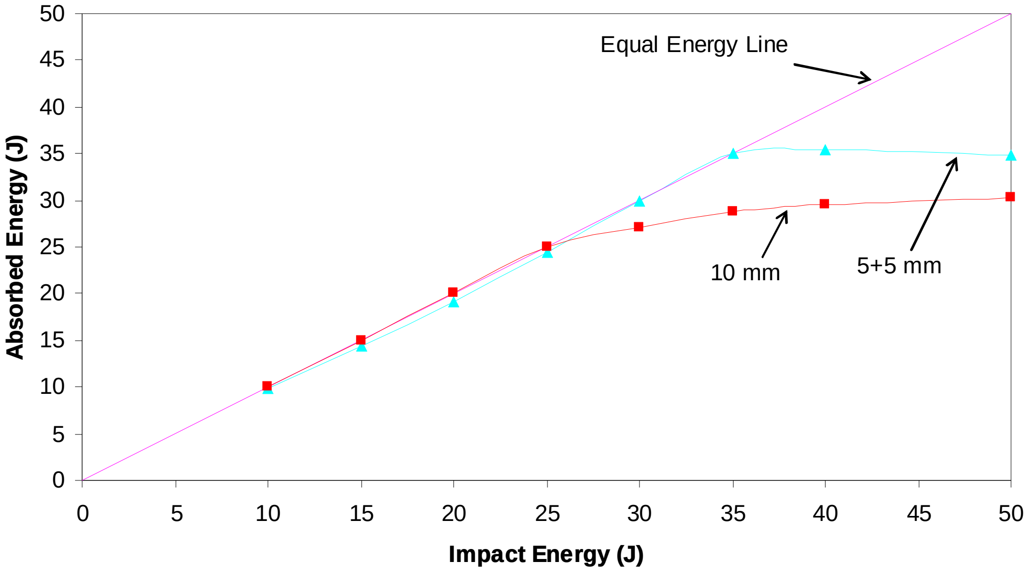


Figure 4.23 Absorbed energy-impact energy diagrams of the sandwich composites with one and two cores.

4.1.3.2 The Core Material Thickness 15mm and 5/5/5mm

This study aims to compare two types of sandwich composites; conventionally designed and three-core sandwich composites which have same thickness in order to study impact behavior of sandwich composite, in this part.

Samples are prepared by using E-glass unidirectional mats as reinforcement and AIREX-PVC foam C.71.55 as core materials, are cured at 80 °C for 8 hours. The specimens consist of six layers and the stacking sequences of sandwich composites were [0º/90º/0º/15mm/0º/90º/0º] and [0º/90º/5mm/0º/5mm/0º/5mm/90º/0º]. The results are obtained after impacted specimens of the sandwich composite at 10J, 15J, 20J, 25J, 30J, 35J, 40J, and 50J energies in the following titles:

- Contact force-impact energy curves
- Deflection-impact energy curves
- Time-impact energy curves
- Absorbed energy-impact energy curves

4.1.3.2.1 Contact Force -Impact Energy Curves. Contact force-impact energy diagram explains the difference between two types of the specimens which consist of 15mm, 5/5/5mm core material as shown in the Figure 4.24.

The specimens have same thickness in conventionally designed and three-core. Contact force for samples of sandwich composite with three-core is lower than conventionally designed sandwich composite. On the other hand, contact force decreases by increasing the core number; the curves show only peak values of contact force during impact energy. The contact force increases by increasing the impact energy to 35J energy because the perforation threshold occurs for one and three cores.

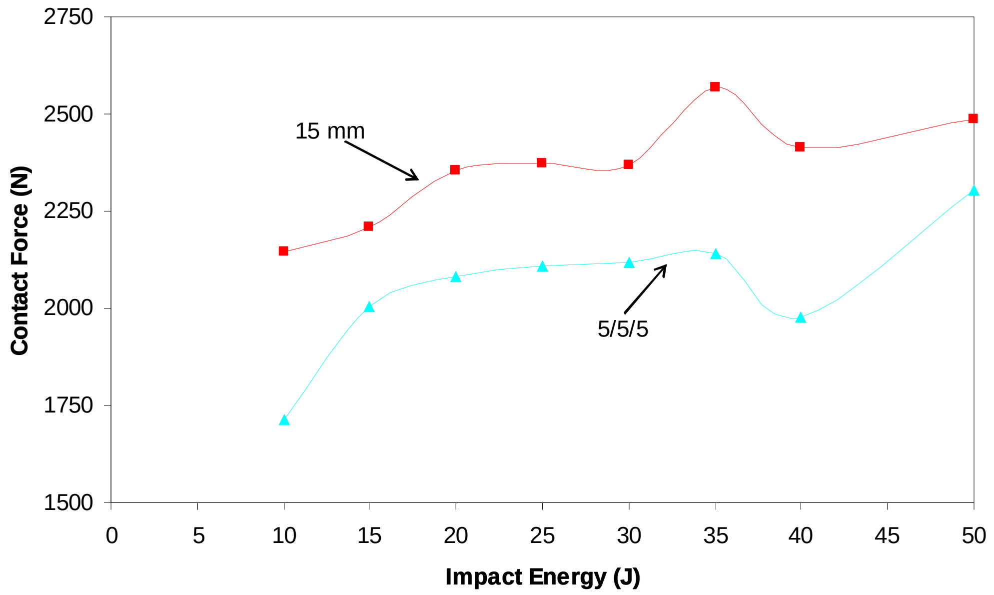


Figure 4.24 Contact force-impact energy diagrams of the sandwich composites with one and three cores.

4.1.3.2.2 Deflection-Impact Energy Curves. The Figure 4.25 explains the deflection-impact energy diagram, by comparing two types of the specimens; the traditional sandwich composite and multi core sandwich composite which consists from same thickness as 15mm core material and 5/5/5mm core material respectively.

The deflection-impact energy of one-core and three-core sandwich composite were compared by using different impact energy. It can be observed from Figure 4.25 that the curves of deflection increases by increasing impact energy until 40J energy after that deflection decreases. The curve has three peaks in multi cores sandwich composite however curve has two peaks in traditional sandwich composite.

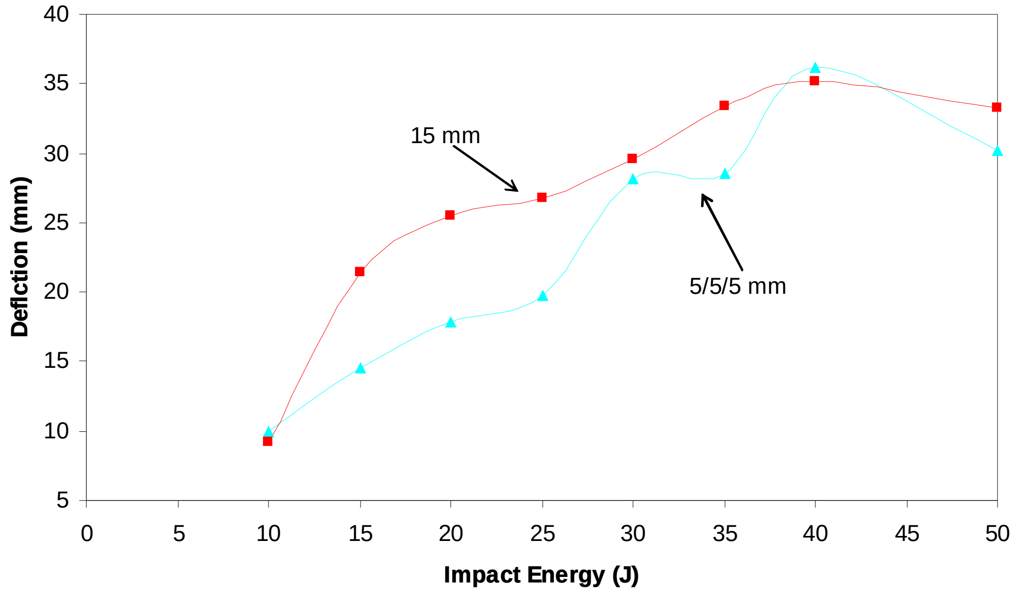


Figure 4.25 Deflection-impact energy diagrams of the sandwich composites with one and three cores.

4.1.3.2.3 Time-Impact Energy Curves. Comparison between one-core and three-core is shown in the Figure 4.26. Time-impact energy diagram for conventional sandwich composite and bonded core sandwich composite which consist of same thickness 15mm core material, and 5/5/5mm cores material, respectively are studied, in this portion of thesis.

The time increases at 15J impact energy, after that decreases by increasing impact energy for conventional sandwich composite however at bonded core sandwich composite the time increases by using 15J energy after that decreases until 25J energy and increases to 30J impact energy after that decreases because of perforation threshold. As seen from the figure, the time has two peaks for conventional and bonded core sandwich composite, the time for conventional is bigger than bonded core sandwich composite until 35J impact energy and the time decreases at 40J impact energy and increases at 50J impact energy.

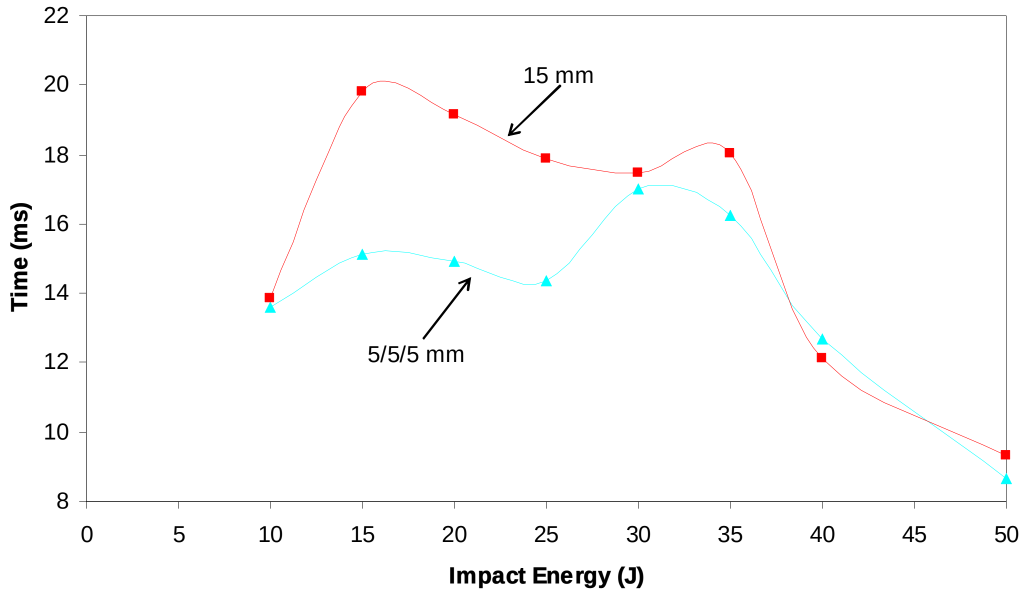


Figure 4.26 Time-impact energy diagrams of the sandwich composites with one and three cores.

4.1.3.2.4 Absorbed Energy-Impact Energy Curves. Absorbed energy-impact energy diagram is shown in the Figure 4.27 in order to compare two types of the specimens which are of same thickness.

The energy profile diagram explains the similarities between traditional sandwich composite and multi cores of sandwich composite. The perforation threshold occurs in 35J impact energy in both the curves for one-core and three-core.

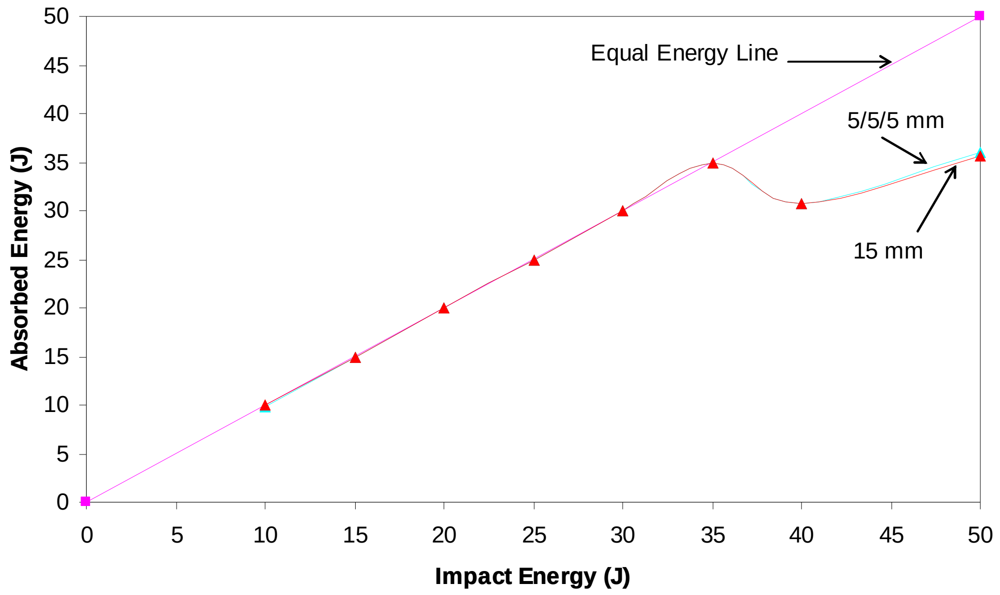


Figure 4.27 Absorbed energy-impact energy diagrams of the sandwich composites with one and three cores.

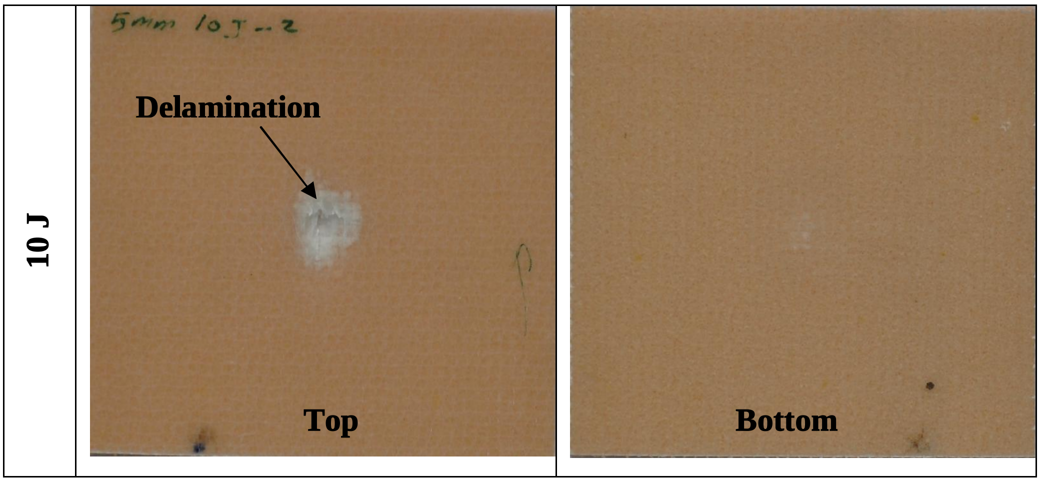
4.2 The Damage of Sandwich Composite Subjected to Impact Loading

Damage occurs in the subjected specimens after impact loading by using 10J, 20J, 35J, and 50J energies, the specimens consist of five types:

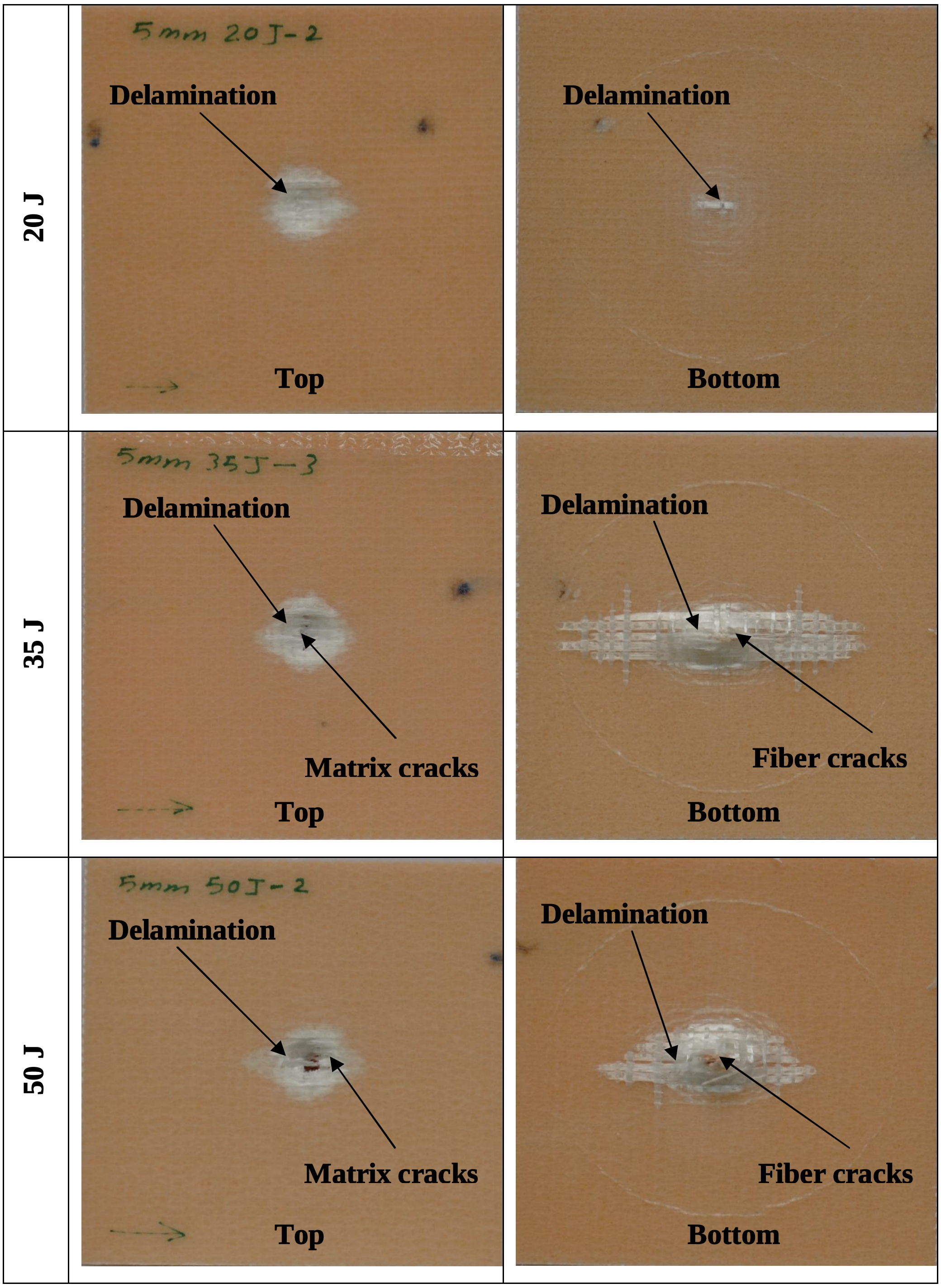
- 5mm core material
- 10mm core material
- 5/5mm core material
- 15mm core material
- 5/5/5mm core material

4.2.1 The Damage of The Sandwich Composites with 5mm Core Material

By visual inspections of top and bottom layers of specimens, the damage mechanism occurs as delamination at 10J impact energy and is observed only on top layers, and there is no damage on bottom layers as shown in Figure 4.28(a). By increasing impact energy to 20J the delamination increases on top layers and occurs in the bottom layers as given in the Figure 4.28(b). At 35J impact energy, matrix cracks and delamination occur in top layers and in the bottom layers, fiber breakage and delamination area increase as shown in the Figure 4.28(b). At 50J impact energy, damage mechanism occurs as matrix cracks, fiber breakage and delamination in the top and bottom layers as seen in the Figure 4.28(b).



(a)



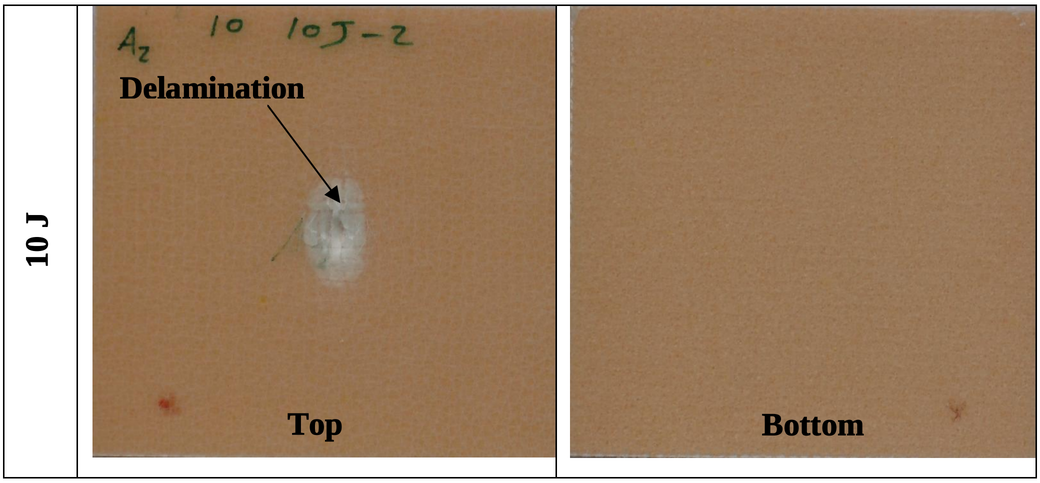
(b)

Figure 4.28 Damages of the sandwich composites with 5mm core material impacted at (a) 10J, (b) 20J, 35J and 50J.

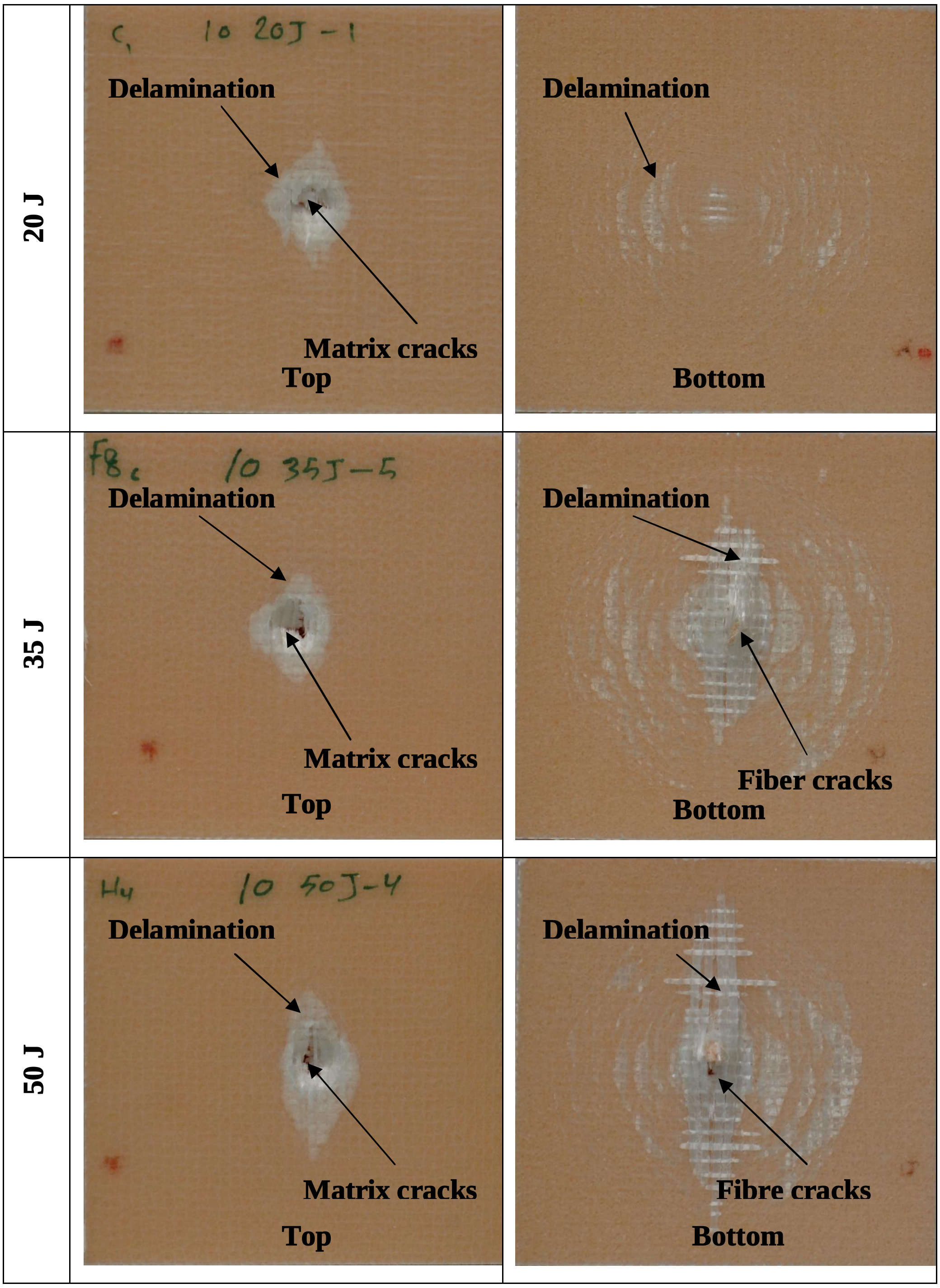
4.2.2 The Damage of The Sandwich Composites with 10mm Core Material

Figure 4.29(a). Explains damage mechanism which occurs only in top skin in the form of delamination and matrix cracks while bottom skin does not have damage at 10J energy. By increasing impact energy to 20J the delamination and matrix cracks increase in top skin and delamination occurs in the bottom skin, as given in Figure 4.29(b).

At 35J impact energy, matrix cracks and fiber breakage occur in top and bottom layers and delamination area increases in the bottom layers as shown in the Figure 4.29(b). However at the 50J impact energy, damage mechanism occurs as matrix cracks, fiber cracks and delamination in the top and bottom layers as seen from the Figure 4.29(b).



(a)



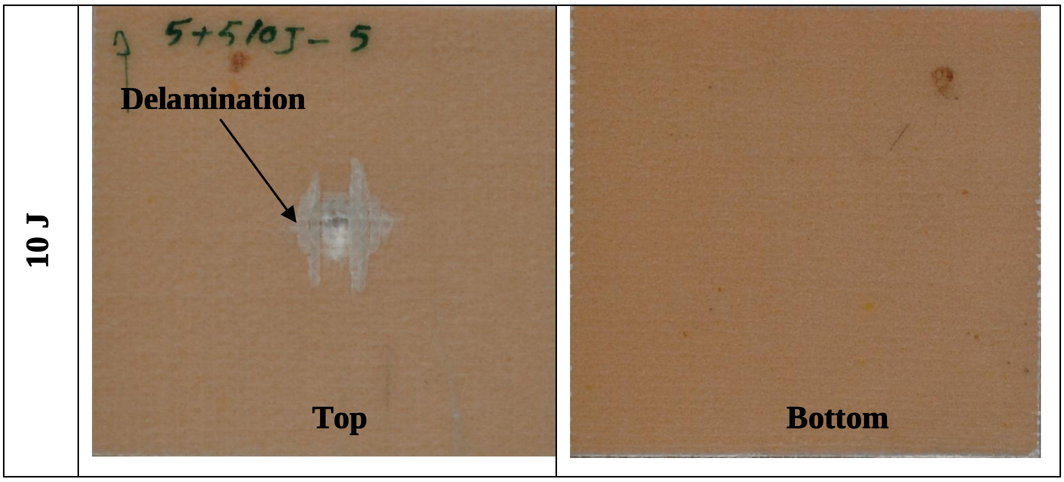
(b)

Figure 4.29 Damages of the sandwich composites with 10mm core material impacted at (a) 10J, (b) 20J, 35J and 50J.

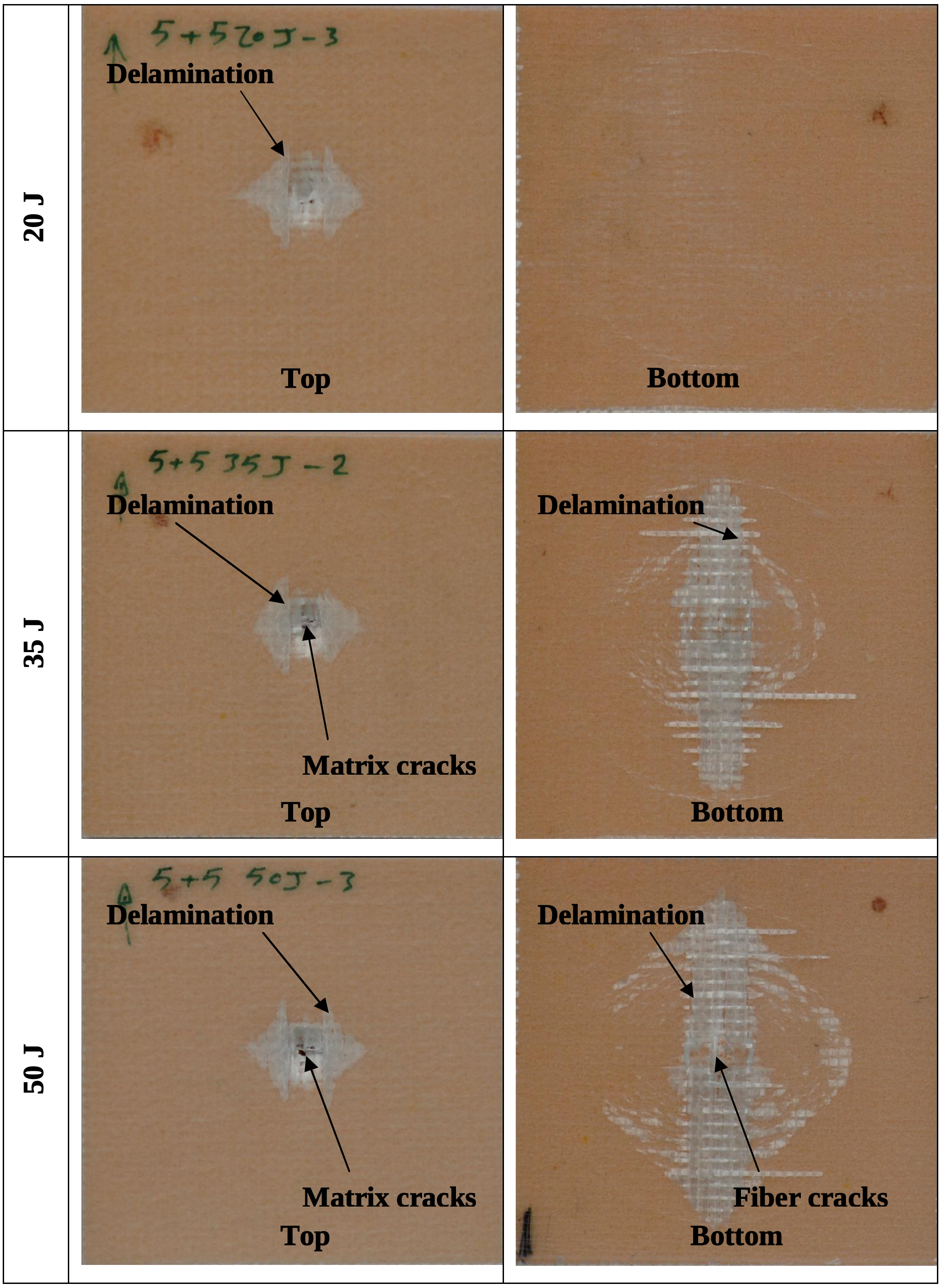
4.2.3 The Damage of The Sandwich Composites with 5/5mm Core Material

In this part, the sandwich composites have two-core and internal sheet. By visual inspections the damage mechanism occurs only in top skins at 10J and 20J such as delamination and matrix cracks and there is no damage in the bottom skins as shown in the Figure 4.30(a) and Figure 4.30(b).

After increasing impact energy to 35J the delamination, matrix cracks and fiber breakage occur in top skins and delamination occurs in the bottom skins as given in the Figure 4.30(b), while at 50J impact energy, matrix cracks, delamination and fiber cracks occur in top and bottom skins as shown in the Figure 4.30(b).



(a)



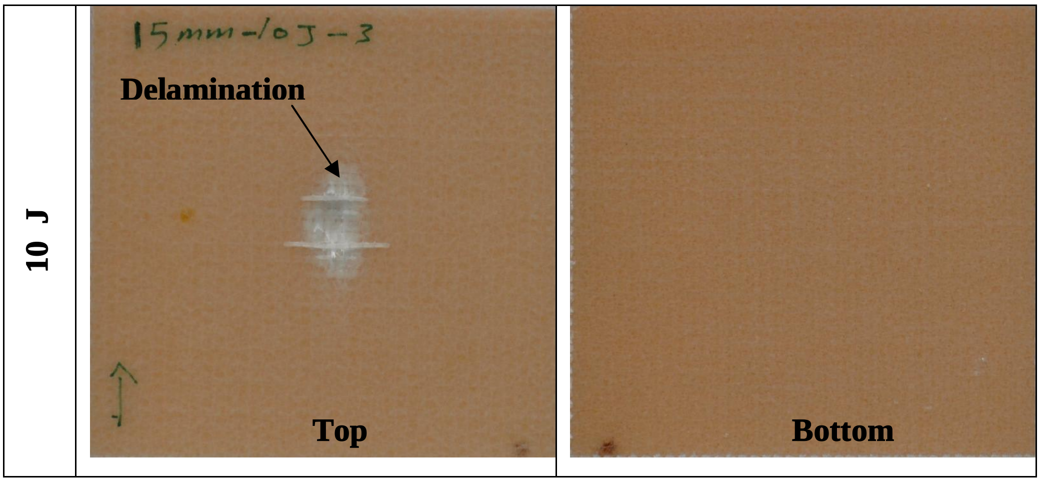
(b)

Figure 4.30 Damages of specimens with 5/5mm core material impacted at (a) 10J, (b) 20J, 35J and 50J.

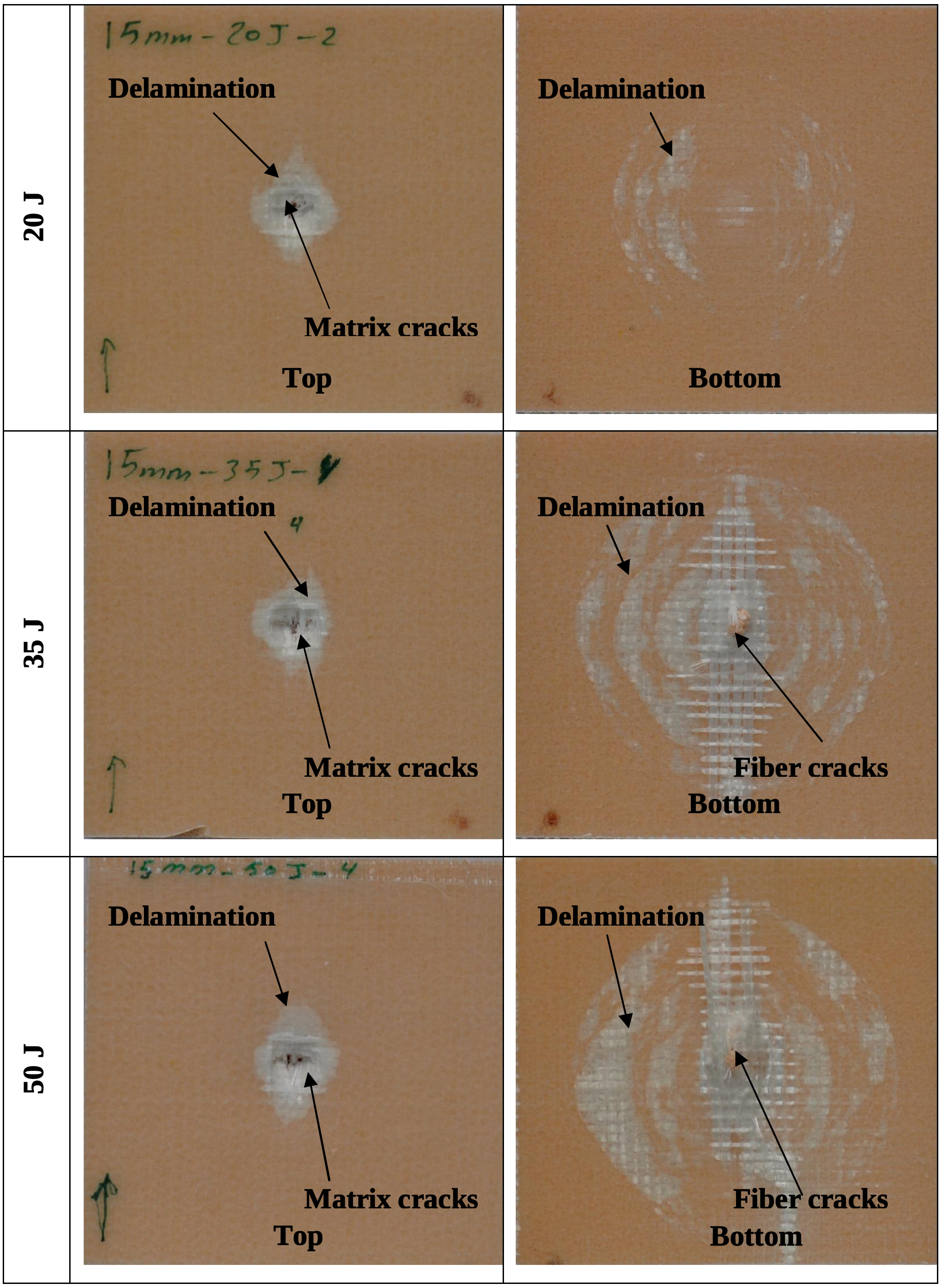
4.2.4 The Damage of The Sandwich Composites with 15mm Core Material

The specimens have one-core with 15mm core material thickness, the damage mechanism occurs only in top skins as delamination while there is no damage in the bottom skins at 10J impact energy as shown in the Figure 4.31(a).

Delamination and matrix cracks occur in top skins however only delamination occurs in the bottom skins by using 20J impact energy as shown in Figure 4.31(b). By increasing impact loading to 35J the damages will be at top and bottom skins, the fiber cracks and delamination area increase in the bottom skins as given in the Figure 4.31(b). However at 50J impact loading the damage mechanism such as matrix cracks, delamination and fiber cracks occur in the top and bottom skins, as shown in the following Figure 4.31(b). It can be noted from Figure 4.31(b), that delamination area increases with increasing impact loading.



(a)



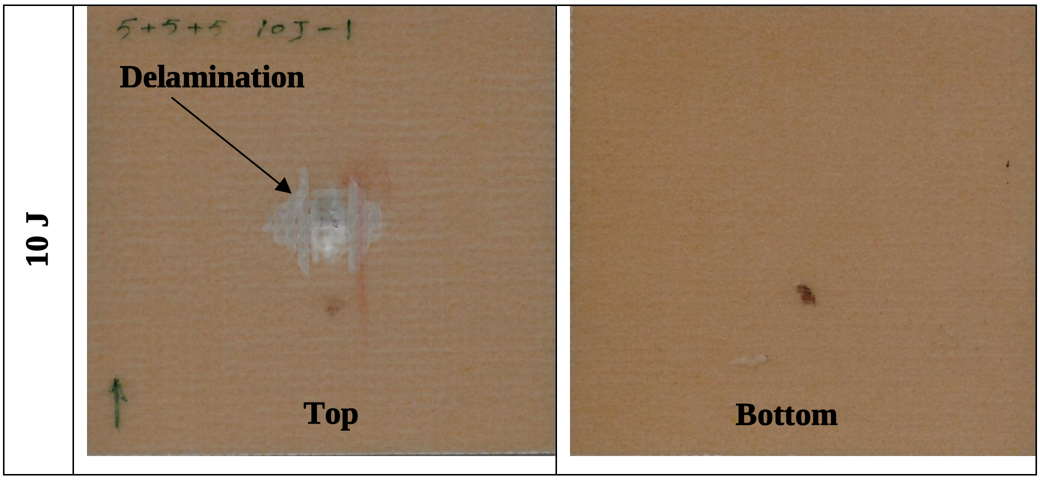
(b)

Figure 4.31 Damages of the sandwich composites with 15mm core material impacted at (a) 10J, (b) 20J, 35J and 50J.

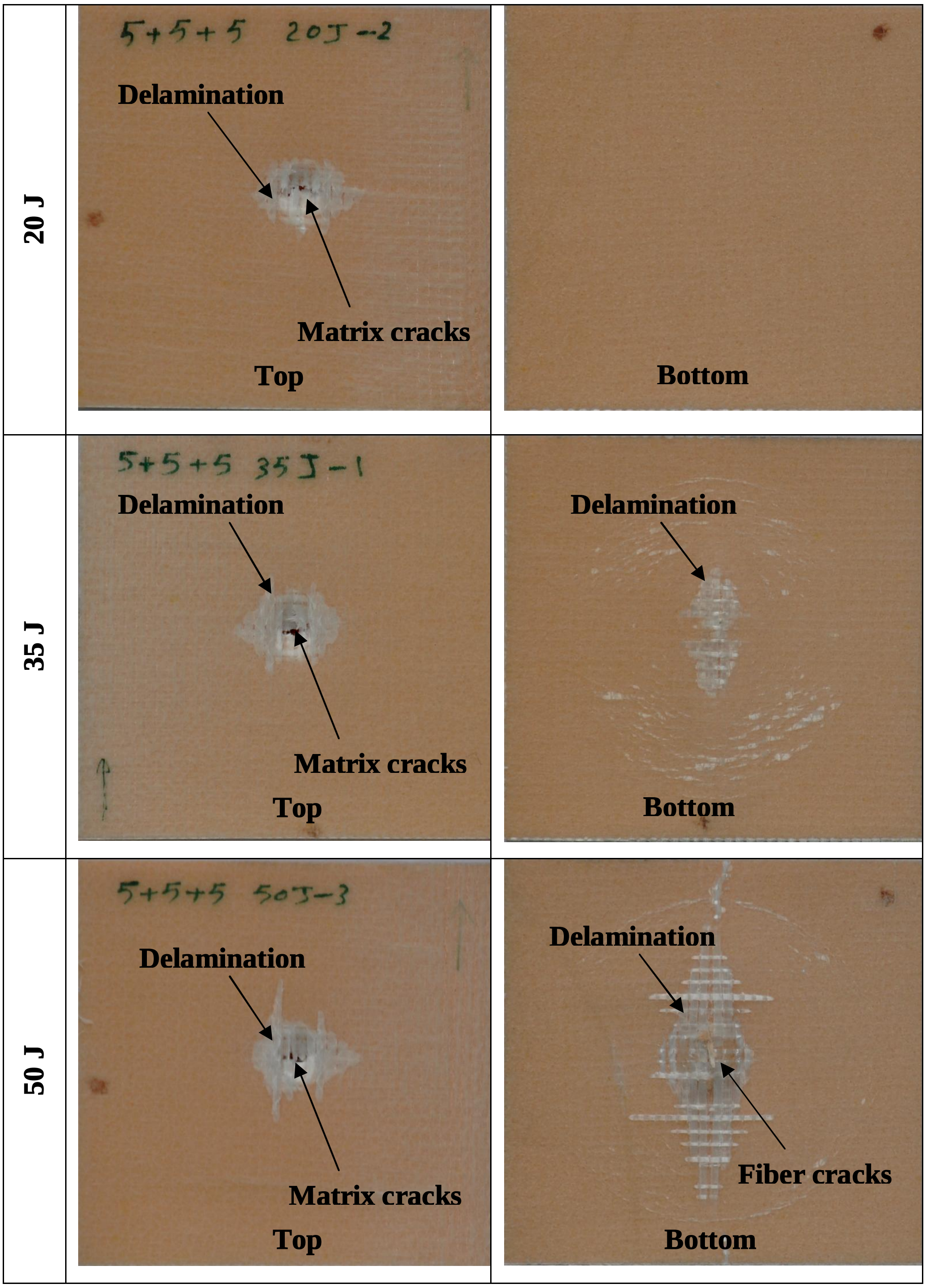
4.2.5 The Damage of The Sandwich Composites with 5/5/5mm Core Material

The specimens have three-core each with 5mm core thickness and two internal sheets in this part, The damage mechanism occurs only in top skins such as delamination at 10J impact loading while delamination and matrix cracks occur at 20J impact energy in top layers and there is no damage in the bottom skins at 10J and 20J impact energies as shown in the Figure 4.32(a) and Figure 4.32(b).

It can be seen from the Figure 4.32(b) that by visual inspections delamination, matrix cracks and fiber breakage occur in top skins however only delamination occurs in the bottom skin at 35J impact loading. By increasing impact loading to 50J, the damage mechanism will occur at top and bottom skins in the form of matrix cracks, delamination and fiber cracks while delamination area increases in the bottom skins as given in the Figure 4.32(b). In other words, the core numbers affect the damage mechanism.



(a)



(b)

Figure 4.32 Damages of the sandwich composites with 5/5/5mm core material impacted at (a) 10J, (b) 20J, 35J and 50J.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Effects of the core material thickness and number with variable thickness or constant thickness on low velocity impact behavior of the sandwich composites are investigated experimentally. Vacuum assisted resin infusion molding (VARIM) was used to manufacture the traditional sandwich composite (0/90/0/core/0/90/0), two-core sandwich composite (0/90/core/00/core/90/0) and three-core sandwich composite (0/90/core/0/core/0/core/90/0). Contact force- time, Contact force-deflection, contact force-impact energy, deflection-impact energy, time- impact energy, absorbed energy-impact energy have been obtained and compared for different impact energies and conclusions are drawn from the results as in the following:

- By increasing core thickness or core number, contact force values decrease however the deflection values and the time increase.

- Damage area increases by increasing impact energy for all sandwich composites and the damage mode can be seen as delamination, matrix cracks and fiber cracks for high impact energy levels.

- It is observed that the maximum contact force occurs in the traditional sandwich composites however the maximum contact time occurs in the sandwich composites with multi cores.

- Perforation threshold occurs for 35J impact energy in sandwich composite with two-core each 5mm while perforation threshold occurs for 25J impact energy for the ones with one-of 10mm.

- Perforation threshold exists at 35J energy for both sandwich composites with one-core of 15mm and three-core each 5mm.

- Absorbed energy increases by using sandwich composite with two-core of 5mm compared to the traditional sandwich composites with one-core of 10mm. However the absorbed energy in sandwich composite with three-core each 5mm is the same as the traditional sandwich composite with 15 mm one piece core.

5.2 Recommendations

For the future studies, investigation indicated below is recommended:

- Effect of core number on the impact properties by using different core material like balsa wood.

- Investigation of thermal impact response by using different core material numbers.

- Effect of different core material number on the bending analysis by using finite element methods.

- Low velocity impact (LVI) behavior of sandwich composites with different core material number reinforced with different types of fiber (e.g. carbon).

- Environmental effect such as humidity, on the behavior of sandwich composites with different core material number and thicknesses.

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