UNIVERSITY OF SOUTHERN QUEENSLAND

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Report for the final year project

Simulation of impact behavior of polymer composite

Student name: Mehsal Alshammari

Major: Mechanical Engineering

Student ID: [redacted]

Project supervisor: Dr Belal Yousif

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Abstract

Composite materials are widely used for engineering applications due to their unique features and special characteristics. A composite material is made from different components which own different mechanical and physical properties. This composite has an elevated and improved physical and mechanical properties compared to its individual components. When a composite material is used for a specific application, it can be exposed to different types of damages, mainly from impact. Therefore, it is important to investigate the composite behavior during impact loading. This research project aims to simulate the impact behavior of a composite material using the ABAQUS software. The S-glass/Polyester composite laminate plate is selected for simulation under three different impact energy by an impactor with drop heights of 0.5 m, 0.75 m and 1 m. This is to generate three different levels of impact velocity and hence impact energy on the composite plate. In this project, the ABAQUS Explicit with dynamic solver which is suitable for the impact problems is selected for simulation and the Hashin criterion is used to predict damage and failure behavior of the composite plate. The obtained results for three impact energy levels show that a higher impact energy results in a higher deflection of plate at its center, a higher von Mises stress and a higher Hashin damage value for the plate. The simulation results are also validated with corresponding experimental data from the literature and a reasonable agreement between the simulation results and experimental data is observed.

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Chapter 1. Introduction

This chapter is allocated to several aspects about composite materials. It first presents some useful information about the composite materials, their applications and structures, and classification of these type of materials. It then describes the polymer composites and their properties and applications. At the end, the impact force on composites and its behavior on polymer composite materials is discussed.

1.1 Composite materials

A composite material is made by the combination of two or more materials with different mechanical properties. The combined materials produce a composite which its properties are different from each of those components. The composite material can be created for a particular application depends on the mechanical or physical properties that that application requires.

For example, different components can be combined together to create a stronger and lighter composite material. Or other types of materials can be combined to create a water proof or electricity resistance composite material. The reason of wide use of composite materials compared to other traditional materials is that these materials can improve the mechanical, physical and other type of properties of the base components. They can be also used in various application and under different conditions (Twi-global, 2019).

One of the characteristics of composite materials is that their components are not completely mixed together, when creating the composites. Therefore, each component keeps its individual identity in the generated composite material. In fact, the components are combined together to help in the formation of a new material with their effective traits to enhance the properties of produced composite material. This improvement can be in strength, performance or durability (CompositesLab, 2020a).

1.1.1 Structure of composite materials

As shown in Figure 1, composite materials are usually made of two main phases including primary or matrix phase and secondary or reinforcement phase.

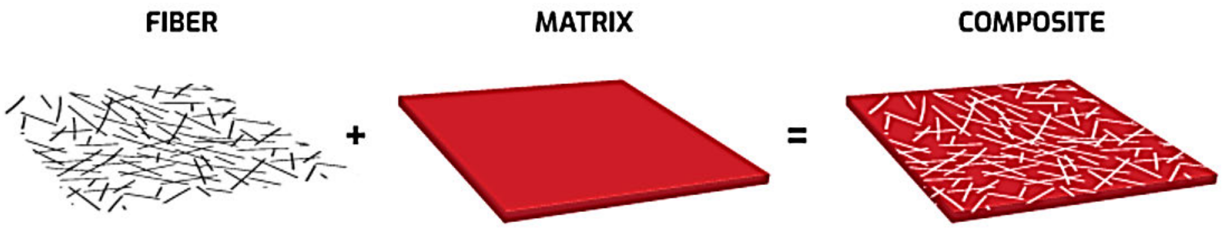


Figure 1. Main phases of a composite material (MechanicalBase, 2018)

The role of matrix phase is to provide a general and unite form and shape for the composite material. This phase is continuous along the composite materials and can be from different materials such as metals, polymers, carbon and ceramics. The reinforcement phase which is dispersed in the composite is used to improve the strength of matrix and composite material. This phase is sometimes named as filler if it is used with the purpose of bulk up for the matrix phase. It is due to the fact that the addition of filler is performed with a low cost without imposing any influence on the composite properties. The interface between the matrix phase and reinforcement phase is usually bonded together with materials which are called interphase.

In a composite, the matrix phase is the bulk material or medium which includes the reinforcement materials which can be in the shape of particles or fibers. In fact, it behaves like a glue which binds the reinforcement materials together. By this way, the matrix phase provides stiffness in the composite material. Otherwise, the reinforcement materials as fibers or particles would not be held in place in the composite (EssentialChemical, 2019).

The matrix phase also transfers and distributes the applied loads on the composites between the fibers in the reinforcing phase. In the case of crack occurrence in the composite materials, it is the matrix phase which prevent it from propagation due its jelly and gluey property. From other roles of matrix phase in the composite material can be mentioned at its protection role. This phase protects the fibers and particles in the composite environment from chemicals and moistures. In addition, it keeps the surface of fibers away from mechanical damages such as degradation by behaving as a shield against chemical and mechanical damages.

The role of reinforcement phase is also important in the composite materials. This phase leads to improvement of properties such as strength and stiffness and other types of mechanical properties of the composites. It also plays an efficient role on the enhancement of other properties of composite materials such as thermal expansion or conductivity (Christensen, 2012).

As mentioned earlier, the reinforcement phase in the composite materials is in the form of fibers or particles. Figure 2 shows the arrangement of this phase in the matrix phase of composites. This arrangement can be continuous and discontinuous fibers, particles and different types of fibrous structures such as fabric or braid which are produced by textile technology (Kutz, 2015).

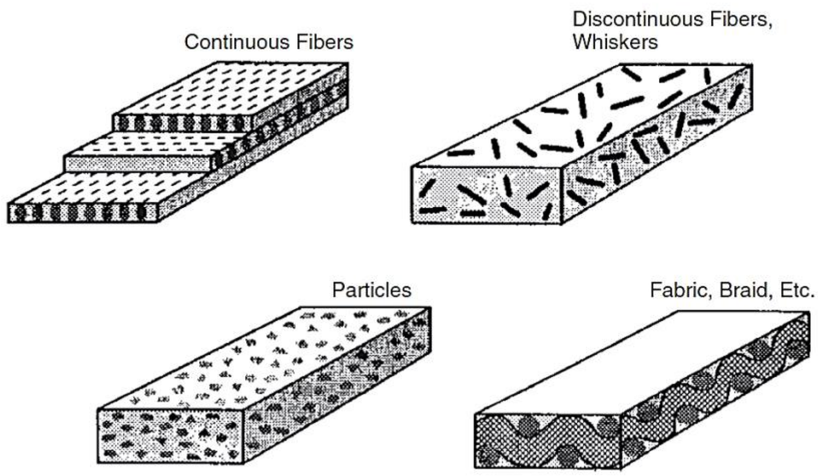


Figure 2. Different forms of reinforcement phase in the composites (Kutz, 2015)

The last phase in the composite materials is the interface or interphase which is located between the matrix phase and reinforcement phase. This phase is also important and significantly affects the mechanical properties of the produced composite materials. It allows for several interactions which happens in the contact of matrix phase and reinforcement phase. Interactions such as mechanical, chemicals or electrical are usually exists in the loaded composite between these two main phases (Jesson and Watts, 2012).

1.1.2 Classification of composite materials

Composite materials can be classified from two main aspects; based on matrix phase material and reinforcement phase material. Figure 3 shows these two classifications. As indicated in this figure, the main types of composite materials based on the matrix are ceramic composites, polymer composites and metal composites. In some other classifications, the type of polymer composites is replaced with organic composites which includes both polymer composites and carbon composites (Yang et al., 2012). The polymer composites are subdivided into other two types of thermoplastics and thermosets composites.

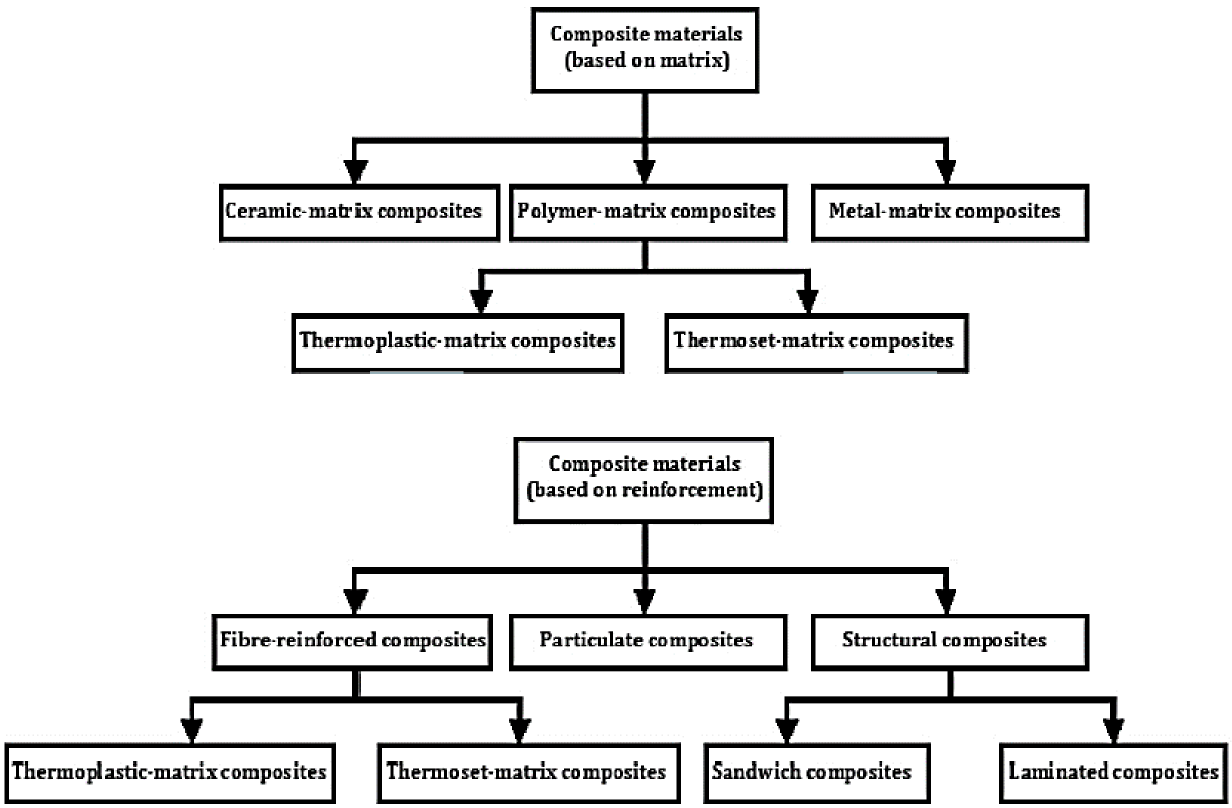


Figure 3. Classification of composite materials (Ibrahim et al., 2015)

With respect to another category based on reinforcement phase material, composites are classified into three main types including fiber composites, particulate composites and structural composite. The fiber composites are individually subdivided to thermoplastic composites and thermoset composites. Similarly, structural composites are also subdivided in two types of sandwich composites and laminated composites.

1.1.3 Application of composite materials

The application history of composite materials by human dates back to many years ago. The first plywood composite material was made in Iraq in 3400 B.C by gluing several wood stripes at different angles. After that, it was in Egypt that death mask was created from linen or papyrus which was soaked in plaster. By getting more experienced, people in these two countries started to reinforce materials with straw in order make stronger bricks, pottery and boats. Later on, in

1200 A.D, people of Mongolia were successful to fabricate bows which was used for hunting or fighting from wood, bamboo, bone or animal horn with pine resin. Their production was very effective and efficient at that time (Twi-global, 2019).

The use of composites became very popular after the industrial revolution. They have been made a significant progress since then to be used in modern industries. Nowadays, these materials are used in aerospace, architecture, automotive, marine, energy, infrastructure, sports and petrochemical equipment (CompositesLab, 2020b). The reason of these wide spread applications is due the several advantages of composite materials compared to the conventional and traditional materials.

Composites have a high resistance against fatigue and corrosion. Their strength and stiffness with respect to their weight ratio is high. It means, for example, the strength of composite materials is higher than the conventional materials, while they are 25 to 40% lighter than conventional materials. Composite materials are more reliable that conventional materials. For this reason, they need less repairs and inspections when used in structures.

Depends on the loading type on the structure, different fibers and reinforcements in the composite materials can be mixed together in a way that they produce a material which can tailor the structure and meet the design requirements against applying loads. These materials offer a high improved torsional stiffness. This provides a high whirling speed for the structure applications which use these materials with low bearing and supporting loads on those structures. They have a resistance against impact, wear and friction.

The aerospace industry was a leading industry in the use of composite materials. The fact is that airplanes, rockets and missiles need to be designed to be as least as possible light, strength and fast. These features were achieved with the use of composites. Nowadays, different types of composites such as glass, carbon and Kevlar fiber are regularly used in various aerospace parts. Fiber composites, in particular, are widely used in aerospace industry due to their efficient properties (Nicolais et al., 2011).

Similar interest in using composite materials exist in the automotive industry. The advanced composite materials such as polymer matrix composites is used in this industry in a large scale.

It is mainly due to the light weight of polymer composites which significantly reduces the fuel consumption and improves the ride quality and resistance against corrosion. It also facilitates the manufacturing of automobile structures.

The architecture and construction industry are also use the polymer composites for many years in several applications such as vanities, cladding, decoration and finishing. This industry was the second large user of polymer composites in 1999 with the use of 35% of the total produced polymer composites in the world. Apart from polymer composites, fiber reinforced composites are also used extensively in construction industry especially in structures. The reason is the high strength of these materials against applied loads. They are also used as an effective alternative for steel in reinforced concretes (Humphreys, 2003).

The use of fiber composites is also wide spread in the sport industry and equipment. Compared to the conventional materials such as steel, stainless steel or aluminum which were already used in fabrication of sport equipment, fiber reinforced composites present significant advantages such as being light. This feature has made these materials attractive in the use of tennis rackets, golf clubs and bikes which need to be light as much as possible to achieve a better performance. Other properties of composite materials such as high elastic modulus and damping absorption are also important in their applications in sport equipment.

1.2 Polymer composites and their applications

As shown in Figure 3, polymers are from the category of composites based on matrix material. These materials individually are weak with a low value of stiffness and also viscoelastic. However, when they get mixed with reinforcing fiber materials, their strength and stiffness properties are improved significantly. The main types of polymers which are used as the matrix materials are thermoplastics and thermosets (Kutz, 2015). This section is allocated to the description of these two main types, their characteristics and applications.

1.2.1 Thermosets

Thermosets are identified as well-bolded three-dimensional structures which are produced after special curing. The term curing is given to a chemical process of polymer fabrication that results in a polymer material with tough and hardened properties. In this process, the polymers are produced by cross linking their chains.

The production of thermoset materials is in the way that they are decomposed instead of being melted at a very high temperature. The composition of resin is modified to change the situations that are required for curing process and also to specify other features in thermoset materials. Moreover, they can be kept in semi-curing condition during a long period.

The flexibility of thermoset materials is very high. As a result, they can be efficiently used as the matrix for the fiber reinforced composites for the purpose of advanced applications. These materials are very useful in the production of chopped fiber composites particularly for the case of using a component which is premixed or molded with fibers with special quality of aspect ratio. This case exists for the production of epoxy, polymer and special resins with phenolic polyamide (Saleh and Koller, 2019).

The application of thermosets is very extensive. These materials are used in aerospace industry, different parts of automobiles, defense system and other industries that are used fiber reinforced composites in a large scale. Epoxy materials which are used in the matrix phase of composite materials have different applications such as in printed circuit boards and related fields. Some types of thermosets are presented in Figure 4. As obvious, epoxy, phenolic and polyester are three main types of thermosets.

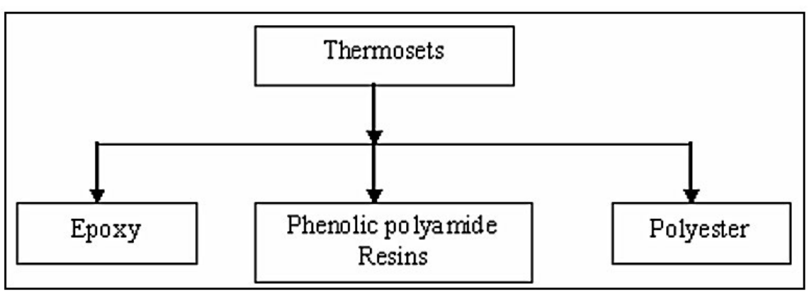


Figure 4. Some types of thermoset materials

Epoxy types of thermoset especially resins have a high application in filament wound composites and are also appropriate for molding prepress. These types of materials are stable in the case of chemical attacks and have a high adhesive property. They have a low value of shrinking under the condition of curing process and do not produce any volatile gases during this process. The mentioned advantages of epoxy resins are, however, along a relatively high cost of these materials. In addition, they are a low melting point and cannot be used in temperatures above 140°C. Therefore, the application of epoxies in the working temperature of higher this temperature is limited.

Other types of thermosets, polyesters, are easily available and cheap. As a result, these types have a high range of application in different areas. For example, liquid polyesters can be kept at room temperature for a long time. The addiction of a catalyst to these materials leads to cure of matrix phase of the composites in a short time. These materials have some applications in automobile and structures.

One type of polyesters is the cured polyester which is rigid or flexible and, in some cases, transparent. The main characteristics of polyesters are that they can tolerate the change of working conditions and also can resist against chemicals. These types of thermoset materials can be used at temperature of around 75°C depends on their structure of resin or application conditions. They are also compatible to be used in glass fibers and can be used to reinforce the plastic devices.

After these mentioned types of thermoset materials to be used in the matrix phase of composites, aromatic polyamides can be also used for the matrix of advanced fiber composites in the field of structures. Particularly for the applications in which durable materials for continuous service at temperature ranges between 200 to 250°C are needed.

1.2.2 Thermoplastics

Thermoplastics, on the other hand, have the molecular structure of one or two dimensional. Figure 5 shows some types of thermoplastic materials. It can be seen that thermoplastics are divided into five main types including polyethylene, polystyrene, polyamides, nylons and polypropylene. The main feature of thermoplastics is that they get melts at a high temperature and therefore they have a high melting point. Some special thermoplastics has the melting point of between 6500 and 7250 F (Todd, 2018). The additional advantage of thermoplastics is that they have a reversible softening characteristic at high temperature. Therefore, they can keep their original properties when are cooled. This factor makes the use of compression method in fabrication of molded compounds easy. Of the applications of thermoplastics is that they are used to reinforce resin which create a new class of composites.

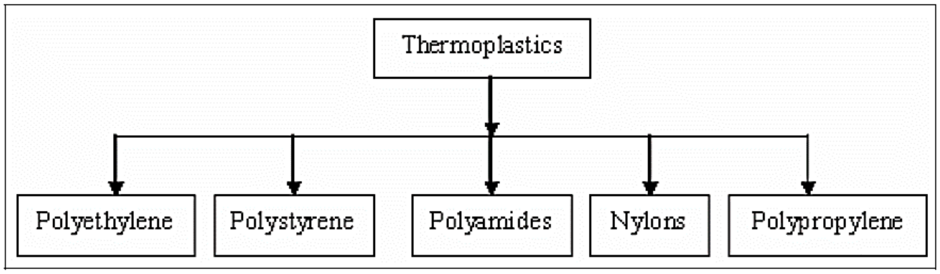


Figure 5. Some types of thermoplastic materials

The use if thermoplastic resins is as the molding compounds which has an application for fiber reinforcement. If the dispersed fiber is used in the matrix, the reinforcement material is isentropic. But if these materials are exposed to molding process, they take a directionally structure in the matrix.

The heat resistance of thermoplastics can be increase using different ways. One way is to addition of fillers which increases the resistance of these materials to heat. The problem of this work is that it leads to the reduction of strength of these types of materials. Regardless of this disadvantage, improvement in other qualities such as rigidity and toughness and also their ability to give up the creep phenomena have made thermoplastics attractive in the category of composite materials. From the advance applications, these materials can be used in automotive control panels and electronic products.

The advantage of thermoplastics in comparison to thermosets is that they do not have any chemical reactions which leads to the release of gases or heat. Production of thermoplastics is only limited to the time which is needed for different processes such as heating, shaping and cooling the manufactured structure. Thermoplastics can be melted repeatedly to produce new shapes and structures from the basic materials. But thermosets do not have this characteristic and once they get formed, they cannot be melted to produce new shape from them. Figure 6 shows the main differences between thermoplastics and thermosets.

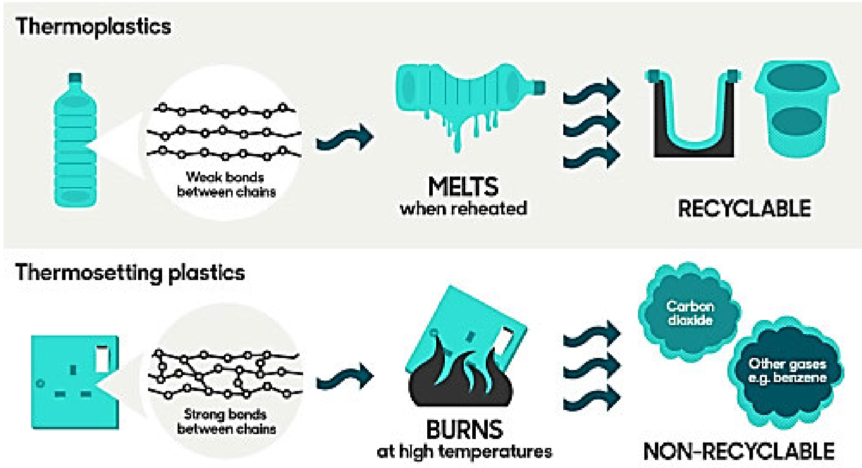


Figure 6. Thermoplastics vs. thermosets (PlasticsMolder, 2018)

The properties of thermosets and thermoplastics differ from some aspects. As mentioned before, thermoplastics are linear polymers with weak molecular bonds. However, thermosets are network polymers with strong molecular bonds. The melting point of thermoplastics are less than the degradation temperature, while it is higher that this temperature for thermosets.

The size of thermoplastics depends on their molecular weight but for thermosets it depends on their crosslink densities. Thermoplastics are recyclable but thermosets are not. Thermoplastics can be used as much as possible by heating or use of pressure. When thermoplastics is exposed to crack, they can be easily repaired. But this case is not easy for thermosets. The continuous use of thermoplastics is lower compared to thermosets in the case of service temperature.

In the case of mechanical properties, thermoplastics are flexible and elastic, while thermosets are rigid and brittle. Thermoplastics have a very higher level of resistance to impact compared to thermosets, almost 10 times higher. The strength of thermoplastics originated from crystallinity while for thermosets it comes from crosslinking (Matmatch, 2020). Some mechanical properties of thermoplastics and thermosets are given in Table 1.

Table 1. Mechanical properties of thermoplastics and thermosets (Kutz, 2015)

	Density g/cm^3 (pci)	Modulus GPa (Msi)	Tensile Strength MPa (ksi)	Elongation to Break (%)	Thermal Conductivity W/m·K	Coefficient of Thermal Expansion ppm/K (ppm/°F)
Epoxy (1)	1.1–1.4 (0.040–0.050)	3–6 (0.43–0.88)	35–100 (5–15)	1–6	0.1	60 (33)
Thermosetting polyester (1)	1.2–1.5 (0.043–0.054)	2–4.5 (0.29–0.65)	40–90 (6–13)	2	0.2	100–200 (56–110)
Polypropylene (2)	0.90 (0.032)	1–4 (0.15–0.58)	25–38 (4–6)	>300	0.2	110 (61)
Nylon 6-6 (2)	1.14 (0.041)	1.4–2.8 (0.20–0.41)	60–75 (9–11)	40–80	0.2	90 (50)
Polycarbonate (2)	1.06–1.20 (0.038–0.043)	2.2–2.4 (0.32–0.35)	45–70 (7–10)	50–100	0.2	70 (39)
Polysulfone (2)	1.25 (0.045)	2.2 (0.32)	76 (11)	50–100	—	56 (31)
Polyetherimide (2)	1.27 (0.046)	3.3 (0.48)	110 (16)	60	—	62 (34)
Polyamideimide (2)	1.4 (0.050)	4.8 (0.7)	190 (28)	17	—	63 (35)
Polyphenylene sulfide (2)	1.36 (0.049)	3.8 (0.55)	65 (10)	4	—	54 (30)
Polyether etherketone (2)	1.26–1.32 (0.046–0.048)	3.6 (0.52)	93 (13)	50	—	47 26)

Note: (1) = thermoset, (2) = thermoplastic.

1.3 Impact on composite materials

The term impact in physics is defined as the collision between two or more bodies. In this case, the bodies interaction can be from the types of elastic, plastic or elastic-plastic. One of the main parameters which determines the influence of impact on bodies in the impact velocity. The higher this velocity is, the larger will be the effect of impact on collided bodies. This phenomenon has different physical effects on bodies such as shock, elastic and plastic wave propagation, fracture and preformation (Razali et al., 2014).

Composite materials are subjected to different types of damages such as fatigue, wear and impact which can occur during manufacturing process or when they are in the service life. When composites are used for a special application, the possible damage is mainly due to the impact and specially delamination. The effect of this damage on composite materials in different.

For example, delamination leads to the formation of a high Interlaminar stress along with a low through thickness strength in the laminated fiber reinforced polymer composites. This problem happens due to the fact that there is no sufficient provided reinforcement through the thickness by the fibers which are located in the plane of laminate. As a result, the composite material only depends on the matrix that withstand load in that direction (Wisnom, 2012).

The effect of delamination in these types of materials is layer separation and formation of a structure similar to mica. This phenomenon is along with the significant reduction of mechanical properties of composite materials. Matrix cracking is another type of damage which usually happens with delamination under the impact loads when the composite materials are in service life. In fact, this damage mainly occurs in composite laminates which are subjected to cyclic tensile loads and impact loads with low velocity. Figure 7 shows the creation of delamination and matric cracking in a sample composite material.

Apart from delamination and matrix cracking which happens due to the impact on composite materials, other types of failure can be also generated from this damage. In fact, the impact damage can be seen created in different cases such as debonding in fiber or matrix, surface micro buckling and fiber breakage. These all types of failure which originate from impact can decrease the performance and efficiency of composite materials.

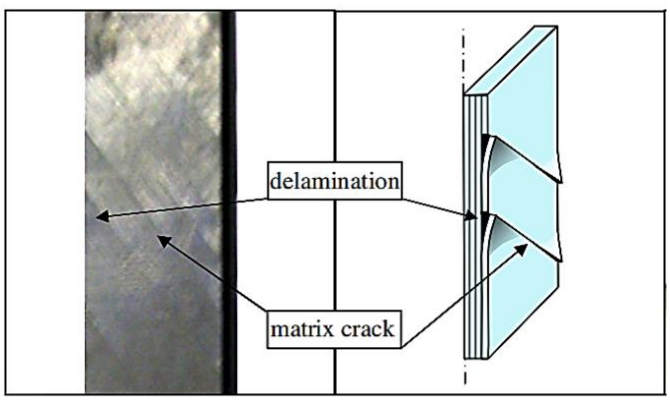


Figure 7. Delamination and matrix cracking in composites (Wisnom, 2012)

The response of composite materials to impact loads is very complicated and difficult to predict due to the lack of available standards or enough performed experimental tests to investigate the effect of impact on these materials. In addition, their behaviors are different from other materials such as metals to compare. For example, for the case of low and intermediate velocity impacts, metals absorb the impact energy by deformation which can be elastic or plastic. This deformation can be permanent in the metal structure but this outcome on the loading capacity of metals is small compared to composites. For the composite materials, this deformation is not almost possible especially the plastic deformation and the impact energy can generate fracture in some of their areas. As a result, the properties of composite materials such as strength and stiffness decrease significantly (Razali et al., 2014).

When impact loading is applied on the fiber reinforced composites, they absorb and dissipate a significant amount of energy by different ways such as elastic process and fracture. A high amount of impact energy is absorbed by elastic process of structure before the start of failure. Several factors exist for this elastic absorption of energy in fiber reinforced composite materials such as mechanical properties of the reinforcing fiber and matrix, the interfacial strength of fiber and matrix, the impact velocity and size of composite structure.

If the impact occurs with a low velocity, the total composite structure absorbs its energy. But if the impact velocity is higher, the main energy is absorbed by a small area of the composite in the vicinity of the contact point. At this situation, the response of the structure is localized to the impact point and the impact effect on the other area of the structure is very small.

The effect of impact on the laminated composites is identified with several damage features such as matrix cracks, delamination and rapture of fiber. As mentioned before, among these damages, delamination is more important because it happens at a low impact load. In addition, the effects of delamination on the composite material are more serious especially on mechanical properties of composite. Delamination causes flexural stiffness degradation and buckling failure of the laminated composites. It also creates the inter-laminar shear stress.

In polymer composites, delamination is the major mechanism in absorption of impact energy. The consequence of this process in polymer composites is the formation of fracture at the weak interface of composite layers. Figure 8 shows the effect of delamination and its distribution in the laminated composite. As it is obvious, the axis of delamination damage is along with the direction of fibers and at the location of plies interfaces.

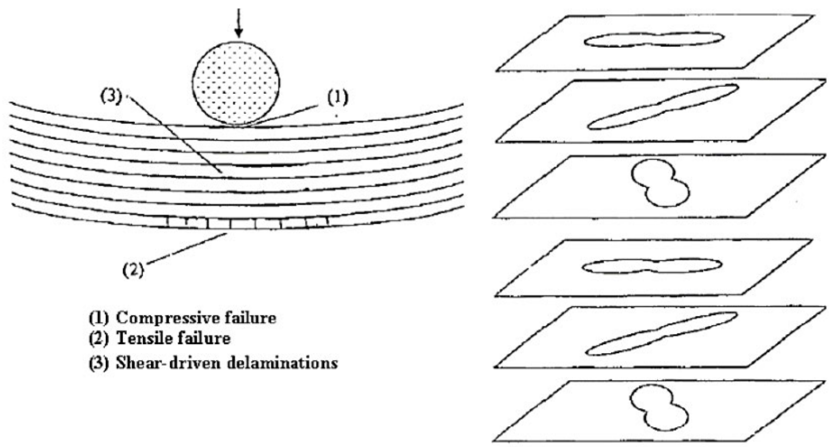


Figure 8. Delamination of composites due to the impact load (Razali et al., 2014).

In order to investigate the effect of impact on the composite structure, the general approach is the separately study two different parameters of impact including impact damage resistance and impact damage tolerance. The first parameter is about the response of the structure to impact and also the created damage on it. The second parameter which is the impact damage tolerance is more about the effect of created damage on the mechanical properties of structure such as its strength and stability (Davies and Olsson, 2004).

1.4 Project aim and objectives

By reviewing the concepts of composite materials, their different types and applications and also the effect of impact of composite materials, it is now possible to mention the purpose of this work and reviewing these concepts. This project aim is to investigate the impact behavior of polymer composites using a computational simulation approach with a 3D modelling software. This will be achieved by the following objectives:

- Review of the basic concepts for polymer composites and their applications in industry
- Review of the impact behavior and its effect on polymer composites
- Literature review on the simulation of impact behavior on composites using a finite element software (ABAQUS)
- Learning the set up for simulation of the impact behavior of polymer composites with ABAQUS software

- Preforming computational simulation under defined boundary conditions and initial values for impact behavior of polymer composites
- Analysis of simulation results and possible validations to confirm the validity of the obtained results

Chapter 2. Literature review

This section presets some of the important research works which are available in the literature about the investigation of impact load and its effect on the composite materials and particularly polymer matrix composites.

(Duodu et al., 2017) used finite element method (FEM) to simulate the effect of impact and especially the penetration process of laminated composites under the condition of high velocity impact. The adopted a three-dimensional rate dependent damage model in order to study the ballistic behavior of impact and response of the fiber reinforced laminated composite. They used damage model to establish the numerical models including the cohesive contact approach. The numerical simulation was performed with ABAQUS software with some user defined functions of FORTRAN implemented in this software. They compared the FEM results with available experimental data and found a good agreement between them. The obtained results showed that the ply angle of laminated composite significantly affect the distribution of damage. They observed that the ballistic resistance and regions of damages in laminated composite are reduced if the angle of ply increases. It was also found that the ballistic resistance and damage properties of laminated composite improve if the thickness of laminate increases.

A new numerical approach including the impact damage prediction and its consequence in wave propagation in laminated composites was developed and presented by (Zhang et al., 2017). They performed this numerical modelling with consideration of delamination and matrix cracking. The obtained results were validated with experimental data which was obtained through different tests on carbon fiber epoxy composite plates. The tests were carried out by the method of drop weight impact tower. They found a reasonable agreement between the simulation results and experimental data for the case of impact response of the composite and also for the wave propagation. It was concluded that in the less damaged areas, the matrix cracking damage creates a lower wave filed compared to the delamination damage.

(Chen et al., 2017) presented a numerical model to predict the effect of low velocity impact on the damage behavior of composite structures with sandwich honeycomb core. Their aim was to study different parameters such as strain rate effect, Interlaminar damage and delamination damage on the composite structures. Apart from the numerical work, they performed experimental tests for validation of obtained numerical results. The experimental test was about the low velocity impact on a carbon fiber epoxy composite with sandwich honeycomb core, same as the selected structure for numerical modelling. Additional parameters such as total energy absorption and the force displacement response to impact were also included in both experiments and numerical modelling. From the numerical technique, the obtained an absorption energy of 10.6 J in comparison to the 11.5 J for experimental results showing a close agreement. Similarly, an error of around 4% was obtained between the numerical results and experimental data for the value of peak force.

(Abir et al., 2017) applied a FEM approach to investigate the damage from impact and also compression after impact (CAI) on composite materials with respect to the actual condition case and no simplification. They used a model for quasi isentropic laminates and obtained results with good agreement with experiments for the different damage aspects such as shape, size and CAI strength. It was shown that the failure due to CAI is affected by local buckling which leads to the damage in fiber and delamination growth. These factors were found to be significant in a rapid load reduction. They concluded that the compressive strength and Interlaminar fracture toughness play an important role on the residual strength of composites and the study of their behaviors help to a better understanding of the mechanism of damage growth.

(Turner et al., 2018) performed a computational and experimental investigation on a 3D woven carbon composite beam under the condition of ballistic impact at various velocity. Their purpose of this study was to understand the mechanism of damage in the composite materials and also the effect of through thickness reinforcement. For the experimental part, different samples were tested under three values of low, medium and high impact velocities. These conditions were to achieve different types of responses and damages on samples such as matrix cracking, deformation, projectile penetration and fiber fracture. For computational simulation part, FEM was applied with ABAQUS software in order to better understanding of different types of responses and damages in the experimental results. It was shown that the existence of through thickness reinforcement hinders the growth of Interlaminar crack in the matrix and also improves the resistance of the carbon composite against impact at low and high velocity. For the impact at medium velocity, however, the fracture of fiber occurred at the position of through thickness reinforcement.

(Elias et al., 2017) applied a numerical and experimental approach to investigate the damage in 3D woven composites due to the low velocity and energy impact. They performed impact tests for various levels of low range energy and evaluated the outcomes by microscopic observation and X-ray technique. The aim of this research work was to study of impact behavior and consequence damages on woven composites. The numerical approach was along with the FEM application with the use of continuum damage model of woven composite when exerted under static loads. The obtained results from numerical modelling which were compared with the experimental data showed a correct description of damage mechanism. It was resulted to find a correlation between the impact energy, damaged area and residual depth.

(Jung et al., 2017) carried out a combination simulation and experimental investigation on polypropylene composites reinforced with glass fibers under the condition of low velocity impact which consideration of Interlaminar fracture toughness. Two types of damage including the Interlaminar and intralaminar created by the impact on the composites were simulated with the use of continuum damage mechanics and cohesive zone models. Different damage features sue to the low velocity impact such as delamination and force displacement were considered at this simulation. Based on the obtained simulation results, they concluded that the applied simulation technique can be used to predict the impact behavior on polypropylene composites reinforced with glass fibers.

A finite element analysis work to simulate the effect of drilling action on a unidirectional carbon fiber reinforced plastic (CFRP) was performed by He et al. (2014). They modelled a three-dimensional sample of CFRP for drilling process using ABAQUS software. An equivalent homogeneous anisotropic material work piece was produced with this software with elastic-failure behavior. The Hashin criterion was used to simulate the failure of the model. The aim was to analysis the drilling process which occurs on the CFRP material with respect to the applied thrust force and cutting condition. They compared the obtained simulation results with the available experimental results and achieved a good agreement between them. At the end, they concluded that the thrust force increases with the increase of feed rate. In addition, they found that the thrust force decreases with increase of spindle speed.

Zouggar et al., (2016) conducted a combination of numerical and experimental investigations of S-glass/Polyester composite laminate plate to study its behavior under low energy impact. They first carried out several experimental tests for low energy compacts on composite sample plates under bending set up. The process of impact on the sample tests was performed using a mass which was dropped from a tower. The analysis and data collection were mainly on damage factors such as the impact force, energy dissipation and bending. In the second stage, the used ABAQUS software to simulate the impact behavior on the model of sample tests and to validate the simulation results. The damage analysis due to impact on the produced composite model was investigated based on the Hashin criterion. The focus was on the drop height of the object on the degradation of composite plate and its damage area. They found that there is linear behavior between the drop height and maximum bending and impact force. In addition, they could get a better understanding of the damage on the sample and damage behavior in the inter plies with the help of computational simulation.

Chapter 3. Methodology

3.1 Background

As mentioned in section 1.4, the aim of this research project is to investigate the impact behavior of polymer composites using a computational simulation approach with a 3D modelling software. By reviewing the performed investigations available in the literature in the related field of this project, it can be seen that the ABAQUS software is the most used 3D software for simulation of impact behavior on composite materials. Therefore, this software will be used to study the impact behavior of polymer composites in this project. The alternative use of ANSYS on impact simulation of polymer composites will be also evaluated. After selection of the appropriate software, a real case sample of a polymer composite with specified composition will be selected for simulation. The boundary conditions such as the velocity of impact and the projectile characteristics should be also known for this work. If possible, the obtained simulation results will be compared with available experimental data to validate the accuracy of results.

For the case of simulation of impact on composites in ABAQUS, the value of impact velocity should be first determined whether it is with the type of low, medium and high velocity impact. The ABAQUS/Explicit model is used for this simulation. Other aspect of finite element simulation is to set the geometrical details of the model in case of dimensions and thickness and also the amount of impact load. At the end, the type of boundary conditions, material of the model and conditions for the contact between the composite layers should be also determined.

For this case, a detailed condition for an available experimental model with given geometry, boundary conditions and other aspects can be found and selected for simulation. Using the experimental data, the simulation results can be then validated to check the accuracy. By this way, the percentage of error between the experimental data and simulation results can be calculated and try to minimize it by redoing the simulation or refining the mesh elements until obtaining the best results. Figure 9 shows a sample of produced composite model in ABAQUS for impact simulation which was performed under low velocity impact (Lopes et al., 2014). In this simulation, a completely rigid and fixed support was used. Other considered simulation parameters are explained in this figure.

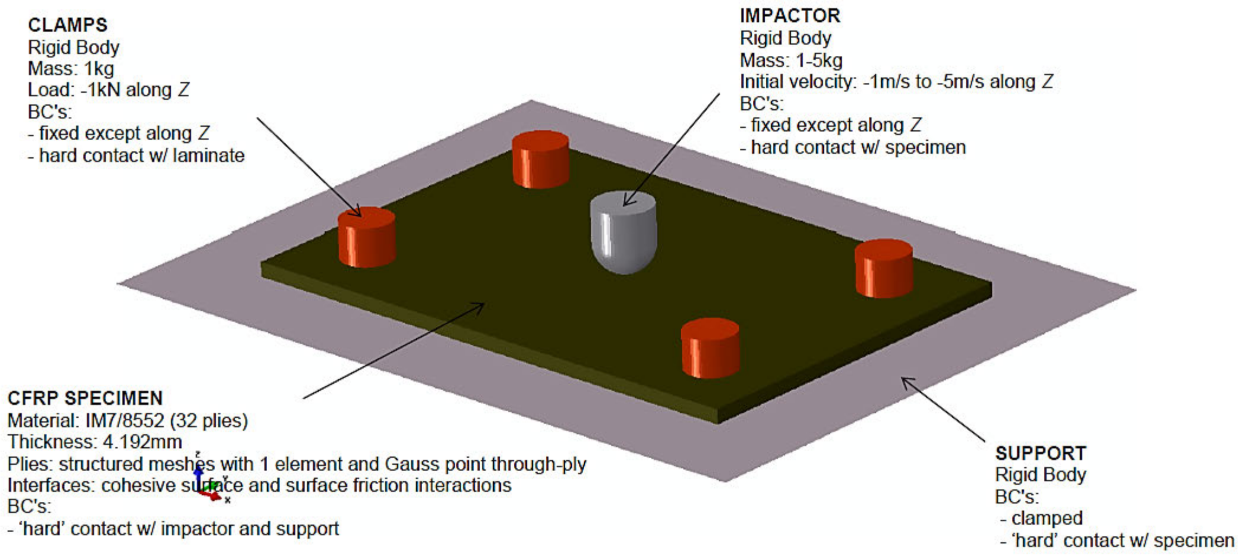


Figure 9. A sample of performed simulation in ABAQUS (Lopes et al., 2014)

As it is seen, the model includes different parameters such as the specimen composite, support which is a clamped rigid body with hard contact with specimen, low velocity impactor with specified mass, amount of velocity and boundary conditions. Four clamps with the material of rubber located at the corners of the model are were also considered in this simulation.

The impactor can be modelled as a rigid body with a defined mass with semi-spherical tip at its impact end with the composite plate. The velocity of this impactor is defined to the downward direction like along negative z axis. It will represent the actual condition in standard tests. In addition, the weight of the impactor should be also considered by activation of gravity along negative z axis.

The damage model in ABAQUS is governed by two equations during the out of plane impact load; one for the matrix and fiber in the composite with a continuum damage model and another for delamination with a cohesive model. For the case of continuum damage, the location of matrix crack and fiber damage should be determined. It can be performed by suing the structural mesh which is aligned with the orthotropic directions of composite material. However, the crack plane is known for the case of delamination.

3.2 Model description

The composite model which is selected for simulation and investigation of impact in this project is taken from Zouggar et al., (2016). It is actually a S-glass/Polyester composite laminate plate which is selected to study its behavior under low energy impact. The experimental set up developed by Zouggar et al., (2016) is shown in Figure 10 in order to have a better description of impact modelling in ABAQUS.

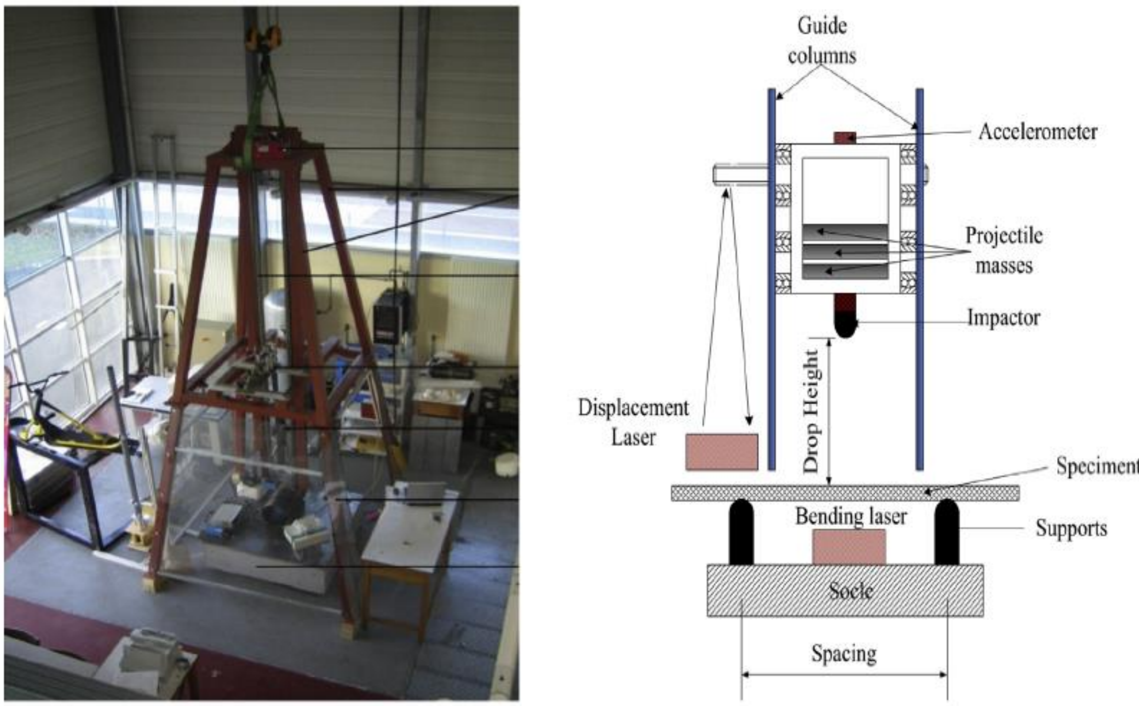


Figure 10. Experimental set up for the low impact test on composite (Zouggar et al., 2016)

In this set up, there is an impactor with a hemispherical shape which has a diameter of 16 mm and mass of 1.825 kg. This impactor is dropped from three different heights on the sample test to study its behavior against impact. Each drop height applies a specific value of energy on the sample. The selected drop values are 0.5 m, 0.75 m and 1 m which generate drop energy of 9 J, 13.6 J and 18.16 J, respectively. The values of drop energy are obtained from the potential energy equation which is mgh.

The composite material under investigation is a S-glass/Polyester composite laminate plate which is stacked with eight conventional plies with stacking sequence of $[0/0/0/90]_s$. It means the first four plies includes three plies with a 0-degree orientation and one ply which has a 90-degree orientation. Same arrangement exists for the second four plies but in a symmetric way. The thickness of each specimen is 4.5 mm including the plies. Therefore, the thickness of each ply is 0.5625 mm. The length and width of specimen are 150 mm and 100 mm, respectively. The mechanical properties of the composite specimen are given in Table 2.

Table 2. Mechanical properties of the composite specimen (Zouggar et al., 2016)

E_1 Young's modulus in X-direction (MPa)	31914.1
E_2 Young's modulus in Y-direction (MPa)	6641.06
E_3 Young's modulus in Z-direction (MPa)	3265.55
G_{12} Shear modulus in XY- plane direction (MPa)	2271.2
G_{13} Shear modulus in XZ- plane direction (MPa)	2247.62
G_{23} Shear modulus in YZ- plane direction (MPa)	2200.47
ν_{12}Poisson's ratio modulus in XY- plane direction	0.15839
ν_{13}Poisson's ratio modulus in XZ- plane direction	0.41522
X_T Tensile strengths in X-direction (MPa)	1544.82
X_C Compressive strengths in X-direction (MPa)	54.88
Y_T Tensile strengths in Y-direction (MPa)	269.56
Y_C Compressive strengths in Y-direction (MPa)	824.58
S_{11} shear strengths in fibre direction (MPa)	112.79
S_{22} Transverse to fibre direction shear strengths (MPa)	65

3.3 Geometry and boundary conditions

The geometry of the composite plate and impactor were produced separately in ABAQUS and then assembled together. For the composite plate, it was first generated by a shell rectangular shape with dimensions of 150 mm × 100 mm in x-y plane and then a thickness of 4.5 mm was given in z plane when defining the material properties. The values of mechanical properties presented in Table 2 are imported for the composite plate as elastic behavior and lamina type.

To define the plies, eight different layers as conventional shell were defined for the composite plate. The thickness of each ply was given as 4.5 mm / 8 = 0.5625 mm. The orientation of each ply with respect to the x axis was defined by the rotation angle based on the stacking sequence of $[0/0/0/90]_s$. The angle of each ply is given in Table 3. Figure 11 shows the produced composite plate and its plies in ABAQUS.

Table 3. Orientation of each ply in the composite plate

Ply number	Orientation (degree)
1	0
2	0

3	0
4	90
5	90
6	0
7	0
8	0

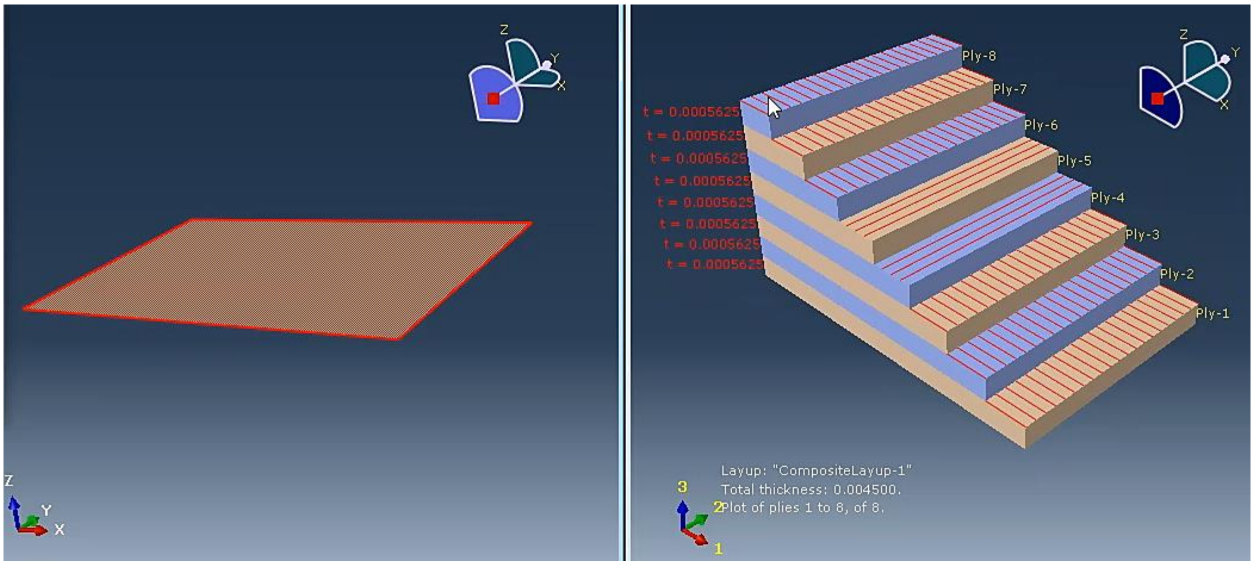


Figure 11. Produced composite plate with 8 plies in ABAQUS

For the impactor, a revolution commend was used to create a cylindrical shape with semi-hemisphere end along z plane as its geometry with 16 mm diameter. The 1.825 kg mass of impactor was given to this geometry by defining a point on it as the reference point. Figure 12 shows the produced impactor in ABAQUS.

After producing the geometry of the composite plate and impactor, both geometries were assembled as shown in Figure 13. It should be mentioned that two approaches can be used to simulate the impact behavior of composite materials; the first method is to model the impactor with the position of specified drop height and then giving it a load gravity. The second method which is applied in this project is to model the impactor tangent to the top surface of composite plate and then giving it an initial velocity. For this case, a surface was defined on the composite plate to define for a tangential behavior and surface to surface contact with the impactor. In Figure 13, it is seen that the impactor is tangent to the composite plate.

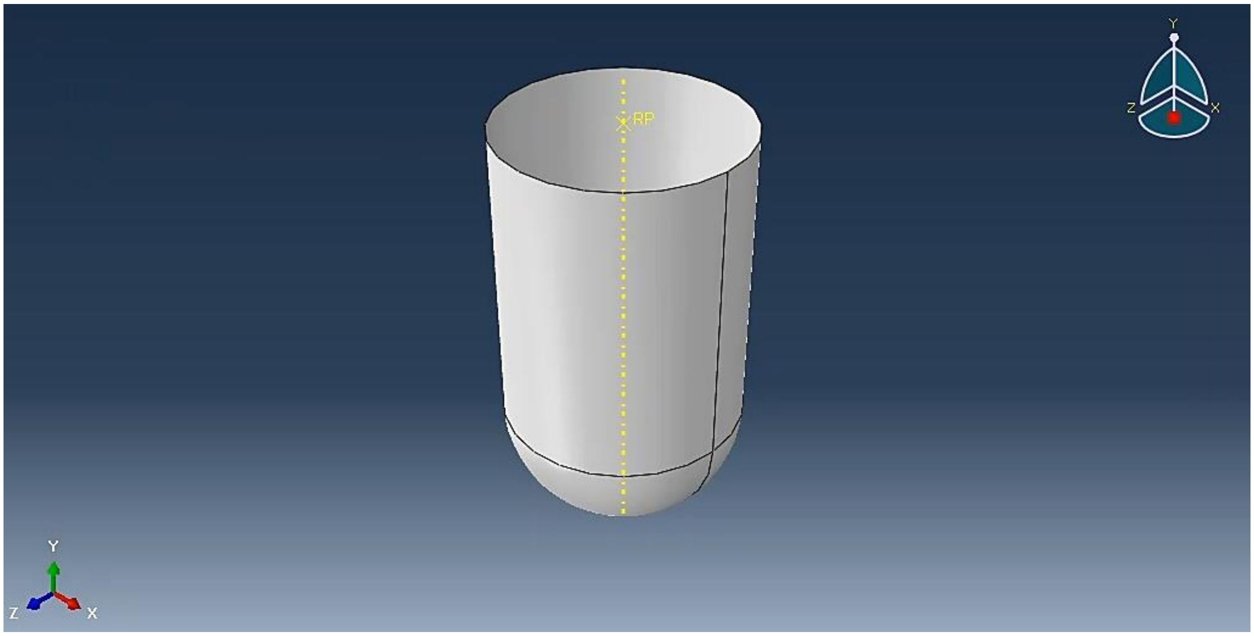


Figure 12. Produced impactor in ABAQUS

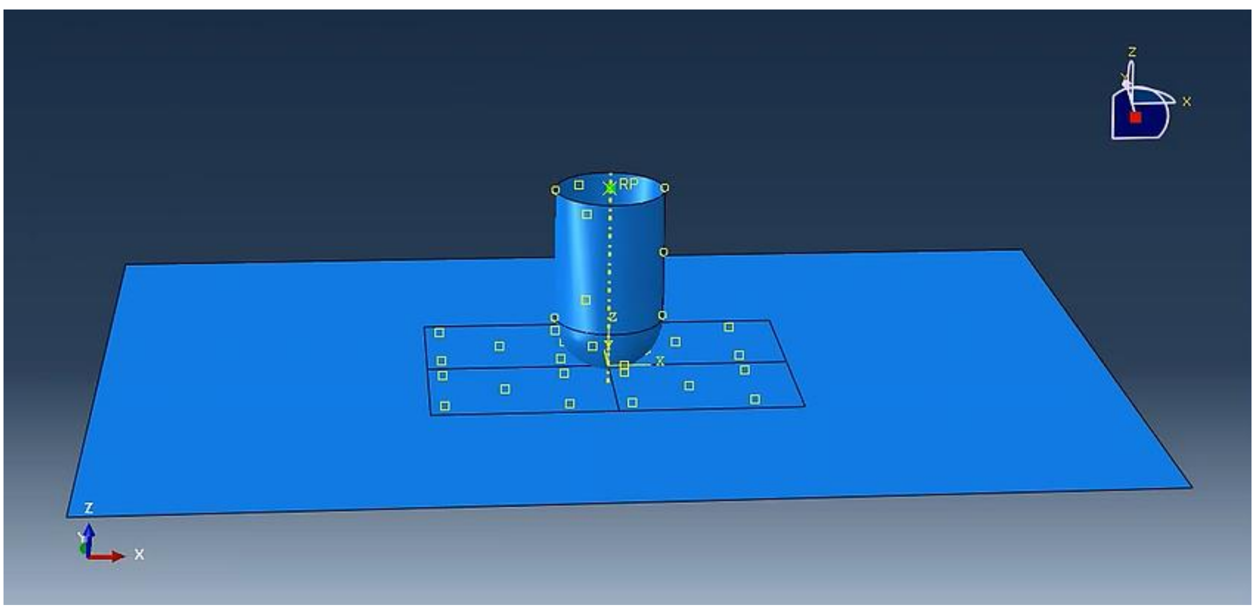


Figure 13. Assembly of composite plate and impactor

For the boundary condition, a pinned boundary condition was defined for the edges of composite plate as shown in Figure 14 to be matched with the experimental set up shown in Figure 10. This is to prevent any displacement along x and y axes and along the direction of impactor (z axis). The boundary condition for the impactor was the release of translation along z direction and giving a velocity of – 3.14 m/s along this axis. This velocity represents the contact velocity of the impactor on the plate when it is dropped from the height of 0.5 m. It is also to generate a 9J impact energy. This velocity can be either calculated from the energy conservation between the potential energy and kinetic energy or from the free-falling equations. If the energy conservation is used, it can be written as:

$$mgh = \frac{1}{2}mV^2 \rightarrow 1.825 * 9.81 * 0.5 = \frac{1}{2} * 1.825 * V^2 \rightarrow V = 3.14\ m/s$$

And if the free-falling object equation is used with zero initial velocity:

$$V^2 - V_0^2 = -2gy \rightarrow V = \sqrt{2 * 9.81 * 0.5} = 3.14\ m/s$$

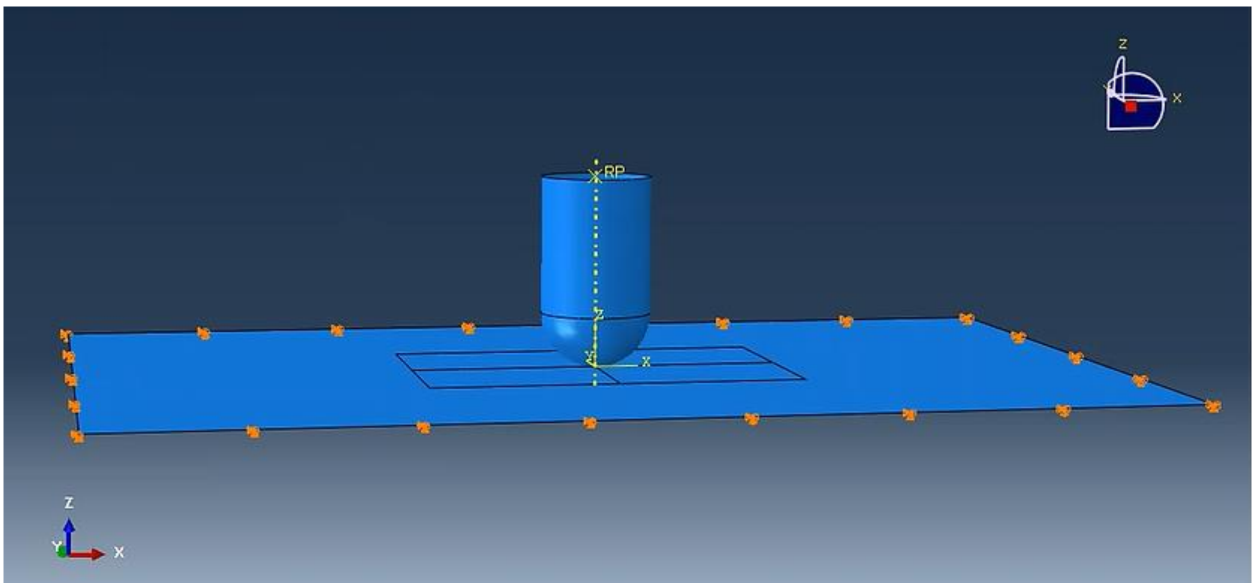


Figure 14. Pinned boundary condition for the composite plate

3.4 Mesh generation

In order to have a better mesh quality, the composite plate was first partitioned in different sections to allow for a finer mesh in the region of impact. The quad mesh element type was applied for this purpose. The grid size for regions near the impact zone was selected to be 2.5 mm and further zones was of 5.5 mm. The total number of grid elements for the composite plate was 2704.

Mesh generation was also performed for the impactor with the grid size of 2.5 mm. The quad element was selected for this purpose and the impactor was meshed with a total number of 543 elements. The produced mesh for the assembly of the composite plate and the impactor is shown in Figure 15.

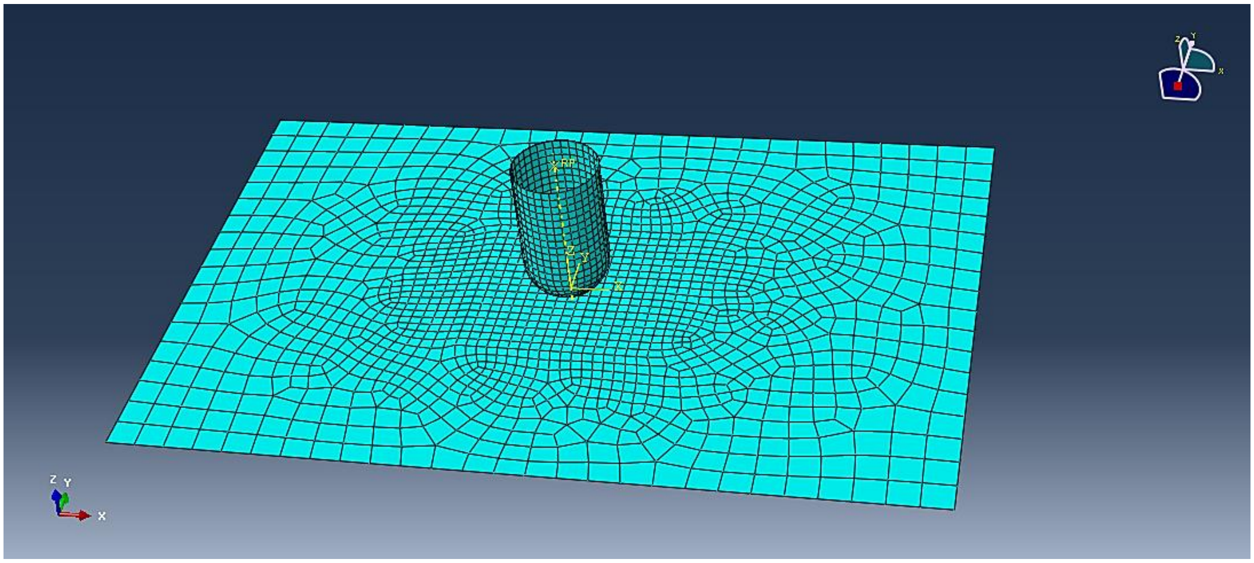


Figure 15. Grid elements for the assembly of composite plate and the impactor

3.4 Numerical procedure

The current simulation was conducted with ABAQUS Explicit method with the dynamic explicit solver which is suitable for the impact problems. The produced geometry of composite plate as lamina was modelled with anisotropic elasticity. Hashin criterion was used in order to predict damage and failure behavior of the composite plate which is developed by the impactor. This criterion determines the failure of composites in four modes; fiber tensile failure, fiber compressive failure, matrix tensile failure and matrix compressive failure. The sect of these equations is written as follows (Zouggar et al., 2016):

- For fiber tensile failure, $\sigma_{11} > 1$:

  $\left(\frac{\sigma_{11}}{X_T}\right)^2 + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} < 1$ → No failure happens

- For fiber compressive failure, $\sigma_{11} < 1$:

  $\left(\frac{\sigma_{11}}{X_C}\right)^2 < 1$ → No failure happens

- For matrix tensile failure, $\sigma_{22} + \sigma_{33} > 0$:

  $\frac{(\sigma_{22}+\sigma_{33})^2}{Y_T^2} + \frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2} < 1$ → No failure happens

- For matrix compressive failure, $\sigma_{22}+\sigma_{33}<0$:

$$\left[\left(\frac{Y_C}{2S_{23}}\right)^2-1\right]\left(\frac{\sigma_{22}+\sigma_{33}}{Y_C}\right)+\frac{(\sigma_{22}+\sigma_{33})^2}{4S_{23}^2}+\frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2}+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}<1$$ → No failure happens

In this set of equations, σ_{ij} denotes for the stress components along x, y and z axes, S_{11} and S_{23} are the allowable shear strength of material in principal directions, subscripts T and C indicate the allowable tensile and compressive strength of lamina, respectively. In addition, X_T and Y_T stands for the allowable tensile strength along two respective material direction. In a similar way, X_C and Y_C denotes the allowable compressive strength along two respective material direction (Zouggar et al., 2016).

Chapter 4. Results

The obtained results for the performed simulation of the impact behavior of composite material are presented in this chapter. It should be mentioned that this set of simulations were performed based on the research paper published by Zouggar et al. (2016) and the following results are presented for three levels of drop heights; 0.5 m (level 1), 0.75 m (level 2) and 1 m (level 3) which imposes a total energy of 9 J, 13.6 J and 18.16 J on the composite plate, respectively.

4.1 Level 1 impact energy

4.1.1 Contours

Figure 16 shows the displacement contour of the composite plate along the impactor motion (z direction) at the time of maximum deflection. It is seen that the center of composite plate has the maximum deflection due to the impactor the maximum deflection of plate center along the impactor direction is around 4.4 mm.

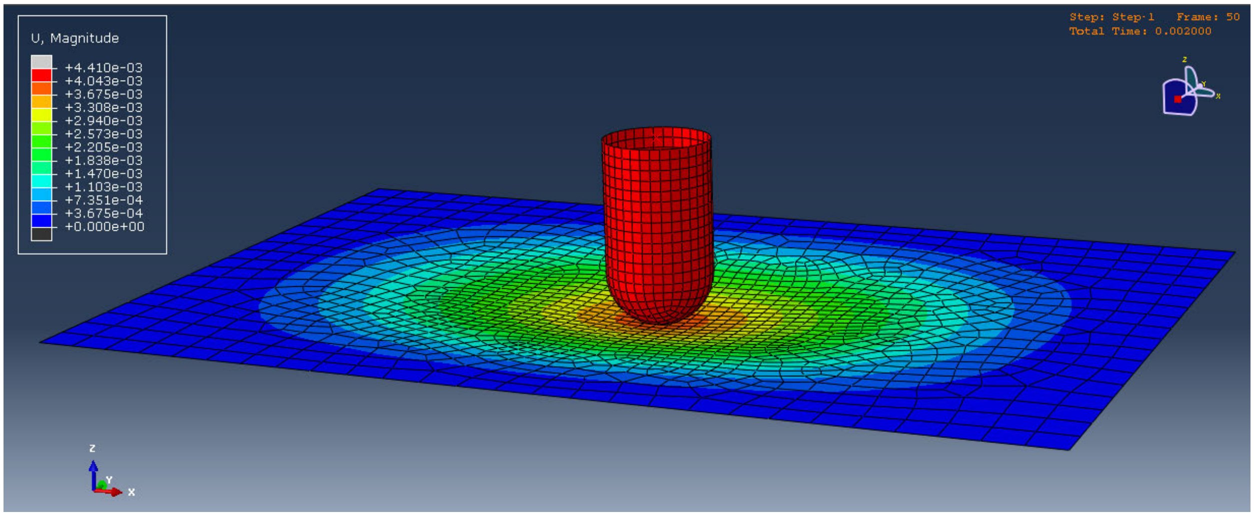


Figure 16. Displacement contour for level 1 impact (legend unit in m)

The contour of von Mises stress is given in Figure 17. The impactor is removed in this plot for a better observation of the location of maximum stress. It can be seen that a high stress is applied on the composite plate at the impact moment. The maximum value of von Mises stress on the center of composite plate is 6.72×10^8 Pa or 672 MPa. The value of stress is reduced at the further regions from the composite center and increases again at the location of pins or constrains.

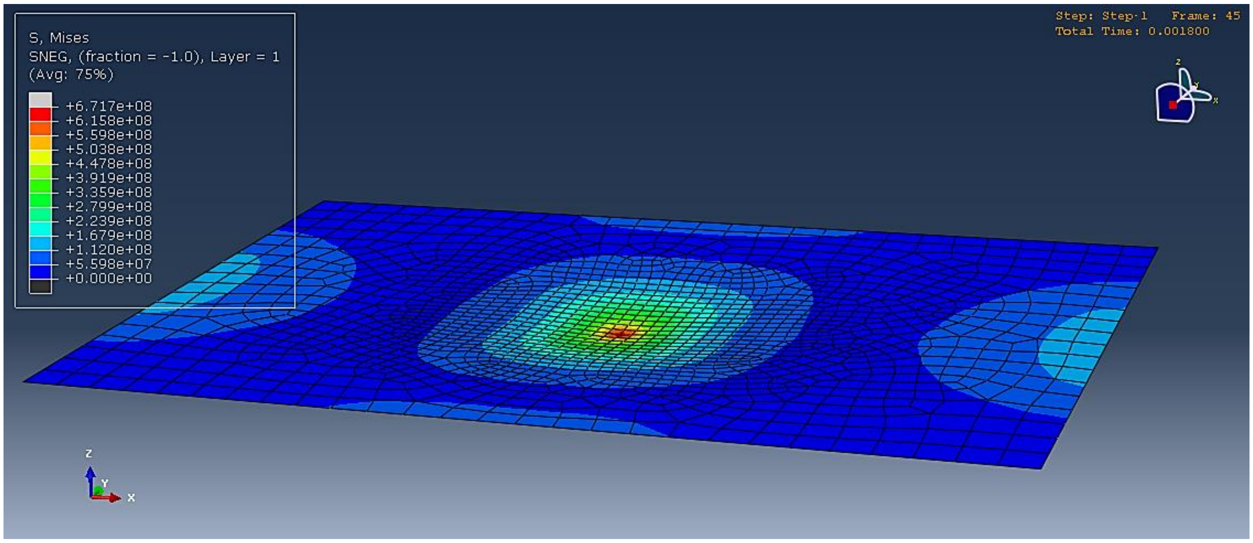


Figure 17. Mises stress for level 1 impact (legend in Pa)

The contours of Hashin criterion for the tensile and compressive damage of the first layer of fiber are shown in Figures 18 and 19. As mentioned in section 3.4 for the Hashin equations, if the value of Hashin criterion is less than 1, no failure happens. With respect to Figure 18, all the maximum value of contour is about 0.25 which is less than 1. Therefore, no failure happens on the first layer of fiber during the tensile stress. However, regarding Figure 19, the value of Hashin criterion is higher than 1 on some areas of the pin location of the first layer. It means the first layer of fiber will be damaged for the case of compressive stress at this area.

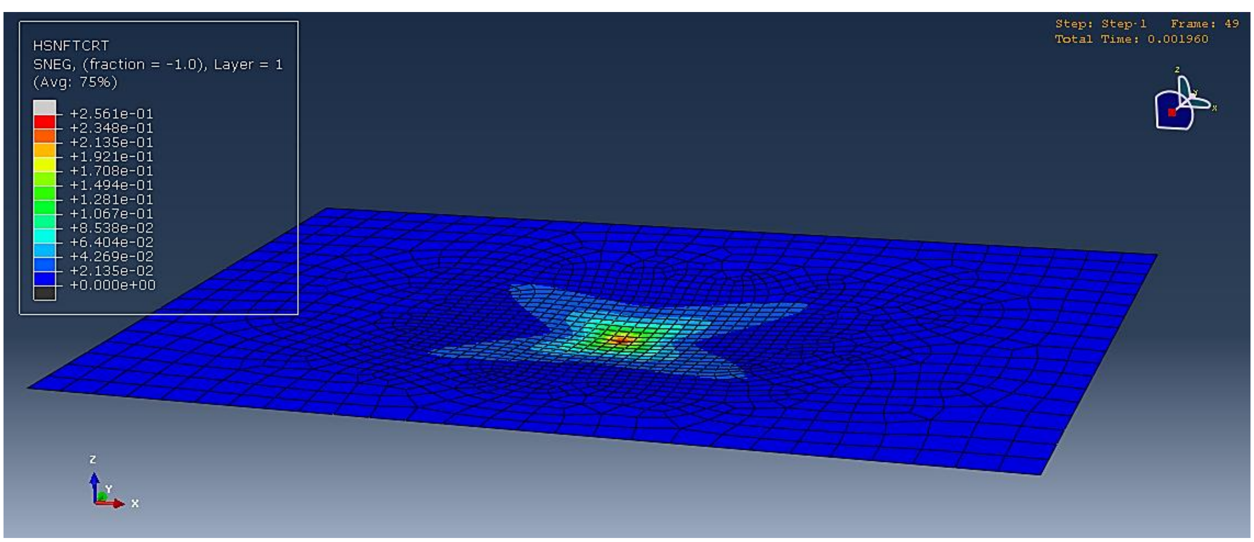


Figure 18. Hashin fiber tensile damage initiation criterion for level 1 impact

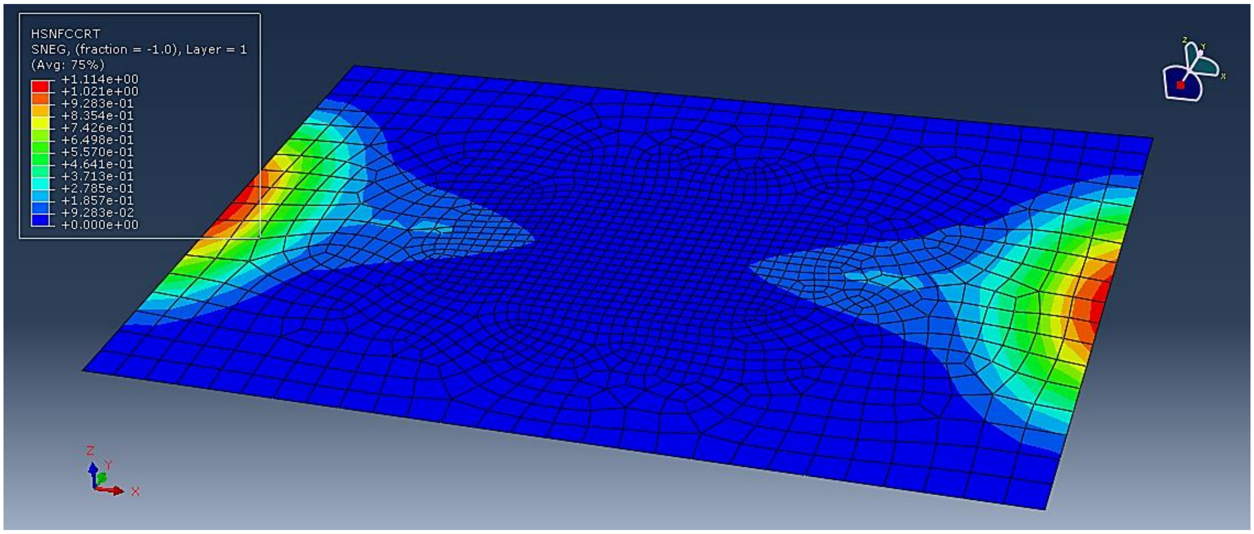


Figure 19. Hashin fiber compressive damage initiation criterion for level 1 impact

4.1.2 Plots

The plot of impact energy during the contact time between the impactor and the composite plate is given in Figure 20. It is seen that the impact process happens in a period of 4 ms and the energy reaches a peak level at the time of 2 ms. The maximum value of impact energy is 8.95 J which is close to the calculation of 9 J value. The value of impact energy has an increasing trend between the period of 0 to 2 ms and then has a decreasing trend between 2 ms and 4 ms.

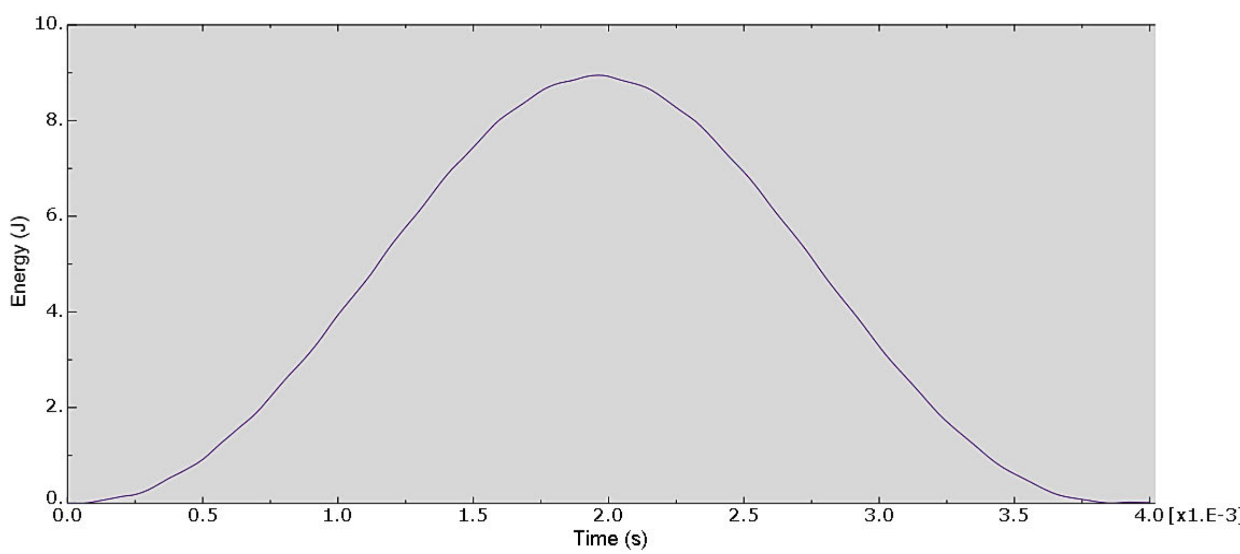


Figure 20. Progress of impact energy for level 1

The displacement plot for the center of composite plate (contact point with impactor) is shown in Figure 21. It is obvious that the maximum displacement of the center of plate happens at the time of maximum impact energy, it means 2 ms. The value of maximum deflection along the direction of impactor contact (negative z axis) is around 0.0044 m or 4.4 mm. The plate returns then to the zero deflection as the impact energy decreases and reaches a zero value at the end.

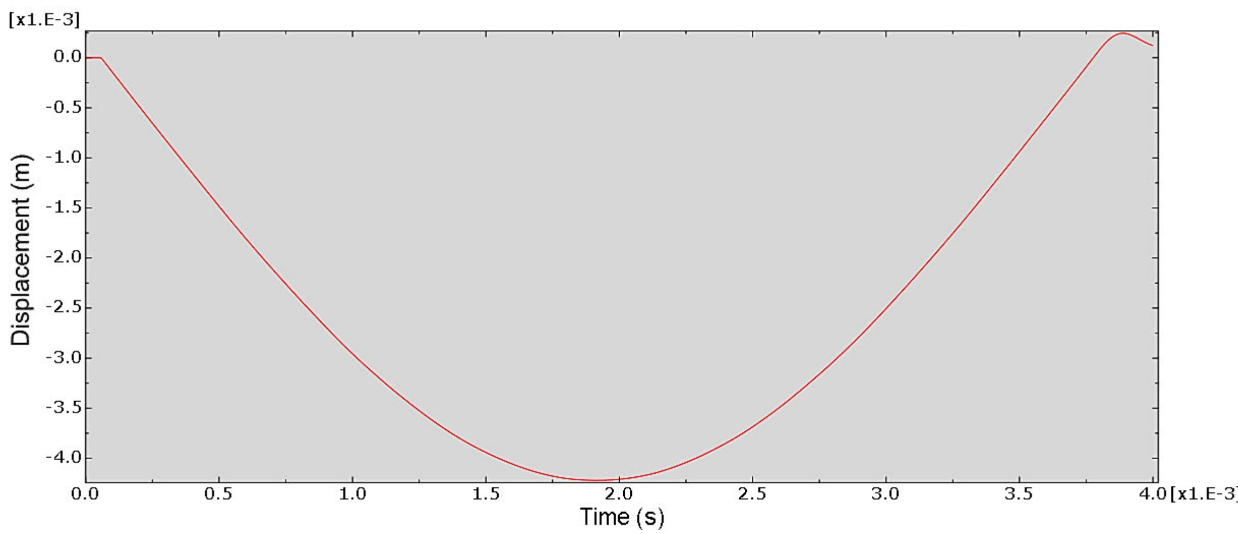


Figure 21. Deflection of the center of composite plate for level 1 impact

4.1.3 Validation

The maximum values of the impact energy and deflection of the plate center from the obtained plots which were presented in previous section are validated with corresponding experimental data reported by Zouggar et al. (2016). This comparison is presented in Table 4 along with the percentage error.

Table 4. Validation of ABAQUS results for level 1 impact

Parameter	Experimental value	Simulation value	Percentage error
Impact energy	9.08 J	8.95 J	1.4 %
Maximum deflection	4.7 mm	4.4 mm	6.4 %

4.2 Level 2 impact energy

This section presents the simulation results for the impact energy of 13.6 J for the impactor drop height of 0.75 m (level 2). The contact velocity of the impactor on the composite plate when drops from this elevation can be calculated from following equation:

$$mgh = \frac{1}{2}mV^2 \;\rightarrow\; 1.825 * 9.81 * 0.75 = \frac{1}{2} * 1.825 * V^2 \;\rightarrow\; V = 3.84\ m/s$$

This velocity is considered for the impactor along the negative z axis in ABAQUS set up.

4.2.1 Contours

The displacement contour of the composite plate along the impactor motion (z direction) at the time of maximum deflection is shown in Figure 22 for level 2 impact. As it is clear, the center of composite plate has the maximum deflection due to the impactor contact. The maximum deflection of plate center along the impactor direction is around 5.2 mm.

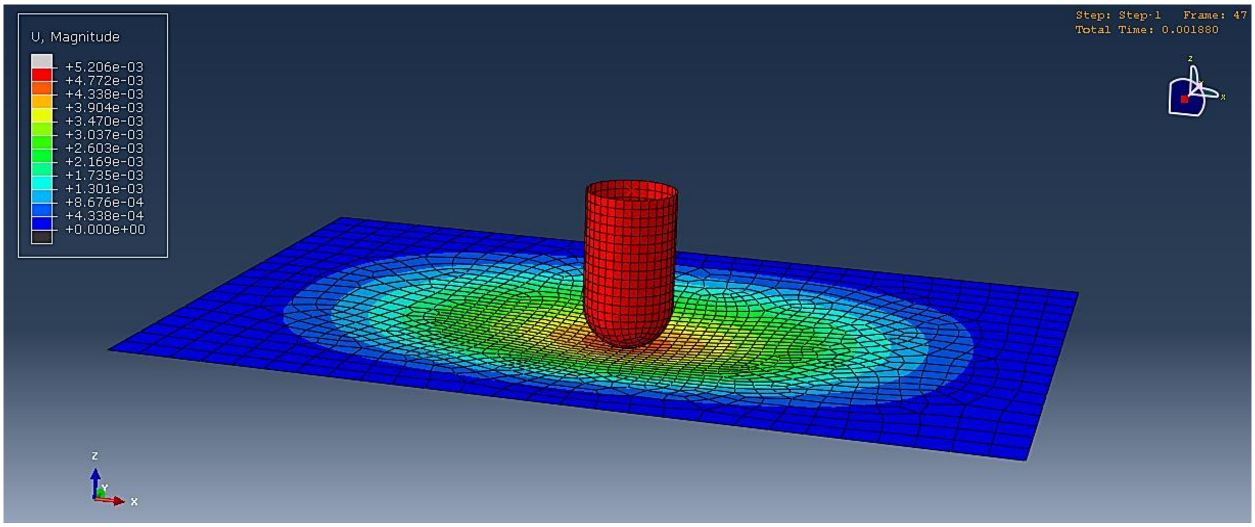


Figure 22. Displacement contour for level 2 impact (legend unit in m)

The contour of von Mises stress for the level 2 impact is presented in Figure 23. The geometry of impactor in hidden in this contour for a better observation of the location of maximum stress. The value of von Mises stress is maximum at the center of plate due to the fact that the highest impact load and energy is applied at this position from the impactor. The maximum value of von Mises stress on the center of composite plate is 8.375×10^8 Pa. This stress value decreases by moving away from the center of plate but increases again at the edges of plate which were defined as constrains.

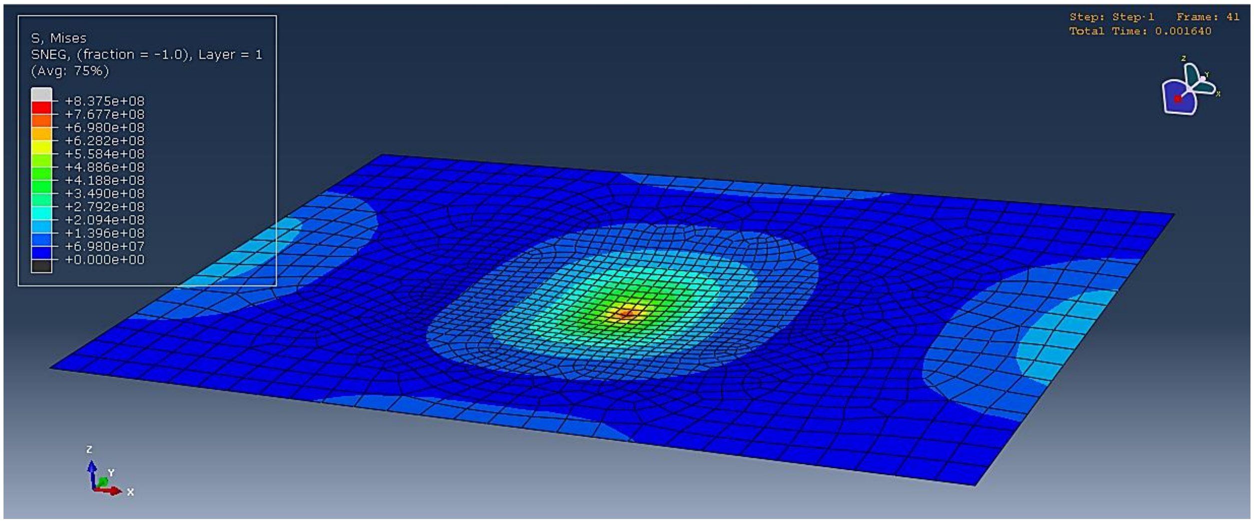


Figure 23. Mises stress for level 2 impact (legend in Pa)

The Hashin criterion contours for the tensile and compressive damage of the first layer of composite plate are shown in Figures 24 and 25 for the level 2 impact. For the case of Hashin criterion, if the values of this criterion in tension or compression is less than 1, there is no failure in the composite. The maximum value of Hashin criterion in Figure 24 for tensile is around 0.4 at the center of plate which is less than 1. Therefore, there is no failure of the composite plate due to the impactor on the first layer of fiber during the generated tensile stress. However, as it is clear in Figure 25, the value of Hashin criterion for compression is 1.57 which is higher than 1 on the constraints. It means the first layer of fiber will be damaged for the case of compressive stress generated by the impactor.

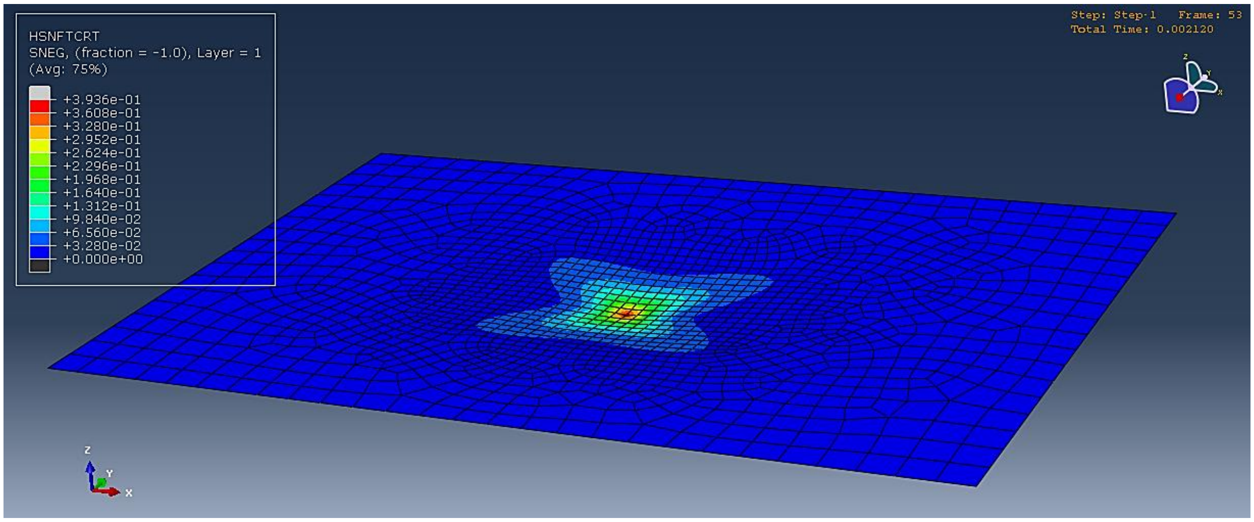


Figure 24. Hashin fiber tensile damage initiation criterion for level 2 impact

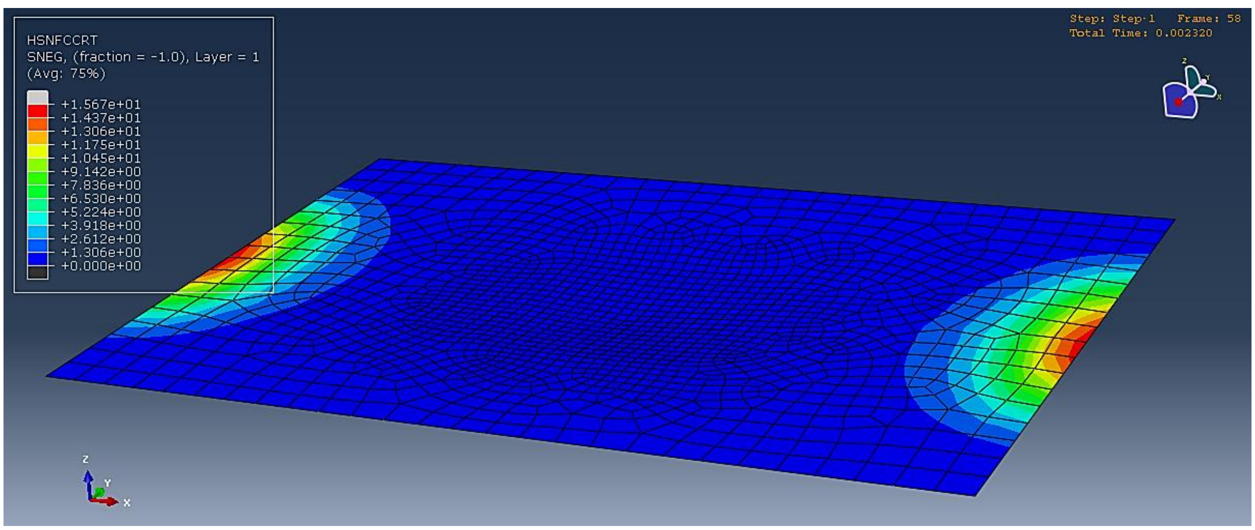


Figure 25. Hashin fiber compressive damage initiation criterion for level 2 impact

4.2.2 Plots

The plot for progress of impact energy during the contact time between the impactor and the composite plate for the level 2 impact is shown in Figure 26. As mentioned before, the level 2 impact has an energy of 13.6 J. with respect to this figure and horizontal axis, it can be said that the contact time of the impactor and the composite plate is 4 ms and the evolution of impact energy happens during this period. It means, it takes around 2 ms from the impact time to achieve the maximum level of impact energy and then another 2 ms for dissipation of this energy. The maximum value of impact energy is 13.4 J which is close to the expected value of 13.6 J.

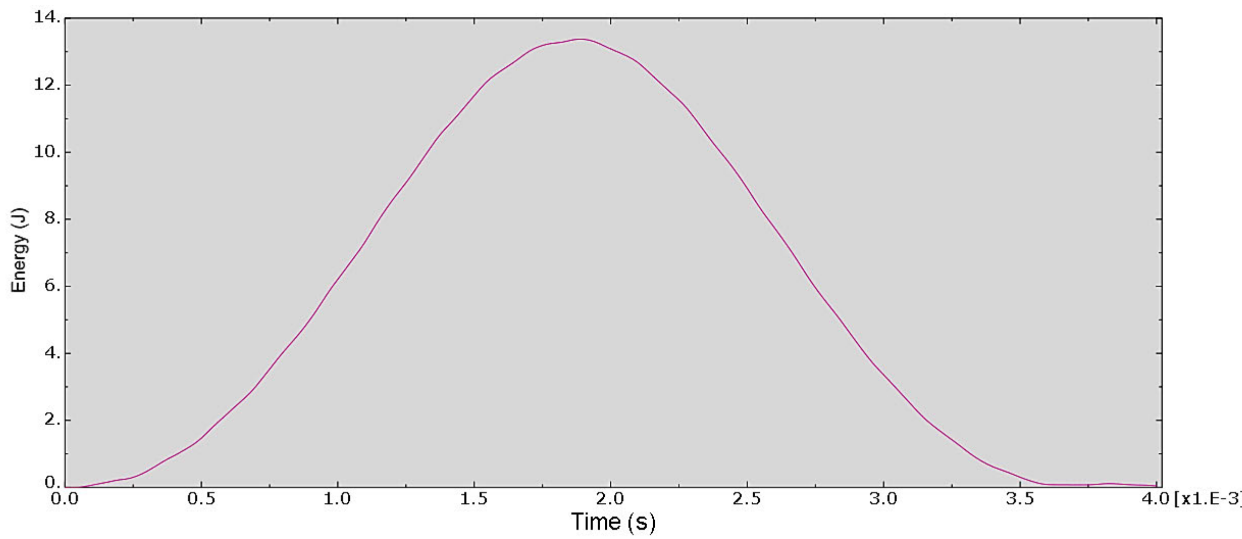


Figure 26. Progress of impact energy for level 2

The displacement curve of the center of composite plate is given in Figure 27. This is the position of impactor contact on the plate. It can be seen that the maximum displacement of the center of plate happens at the time of maximum impact energy (around 2 ms). It is obvious because the plate receives the maximum impact energy at this instance and therefore has the highest amount of deflection. The value of maximum deflection along the direction of impactor contact is around 5.2 mm. The plate restores its initial position to zero deflection as the impact energy decreases to the zero value and fluctuate again.

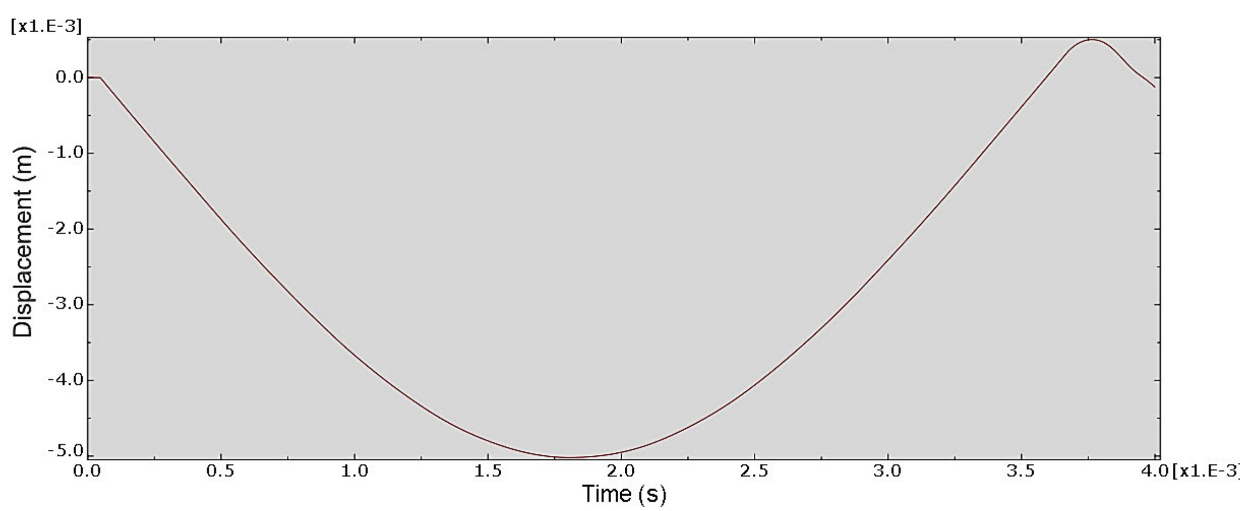


Figure 27. Deflection of the center of composite plate for level 2 impact

4.2.3 Validation

Validation of obtained main results from ABAQUS simulation for the level 2 impact is presented in Table 5. It includes the results of maximum values for the impact energy and deflection of the plate center. These values are compared with corresponding experimental data reported by Zouggar et al. (2016). It is seen that both predicted values from ABAQUS simulation for the maximum impact energy and deflection of the plate center agree well with the experimental data. The calculated percentage error for the value of maximum impact energy is 1.5 % and for the maximum deflection is 11.8 %.

Table 5. Validation of ABAQUS results for level 2 impact

Parameter	Experimental value	Simulation value	Percentage error
Impact energy	13.6 J	13.4 J	1.5 %
Maximum deflection	5.9 mm	5.2 mm	11.8 %

4.3 Level 3 impact energy

Simulation results for the last level of impact energy (level 3, 18.16 J) are presented in this section. The velocity of the impactor when reaching the composite plate from the falling elevation of 1 m is calculated as below:

$$mgh = \frac{1}{2}mV^2 \;\rightarrow\; 1.825 * 9.81 * 1 = \frac{1}{2} * 1.825 * V^2 \;\rightarrow\; V = 4.43\ m/s$$

This velocity is given to the impactor in ABAQUS.

4.3.1 Contours

Figure 28 shows the displacement contour for the composite plate along the z direction (direction of impactor) for the level 3 impact. It includes the deflection results at the frame of maximum deflection. It can be seen that the intensity of deflection is higher at the regions of the plate center. The highest value of deflection for this level of impact is 6.2 mm which happens exactly at the center of composite plate where the impactor contacts the plate. The edges of this plate have zero deflection as they were defined with pinned condition as constraints.

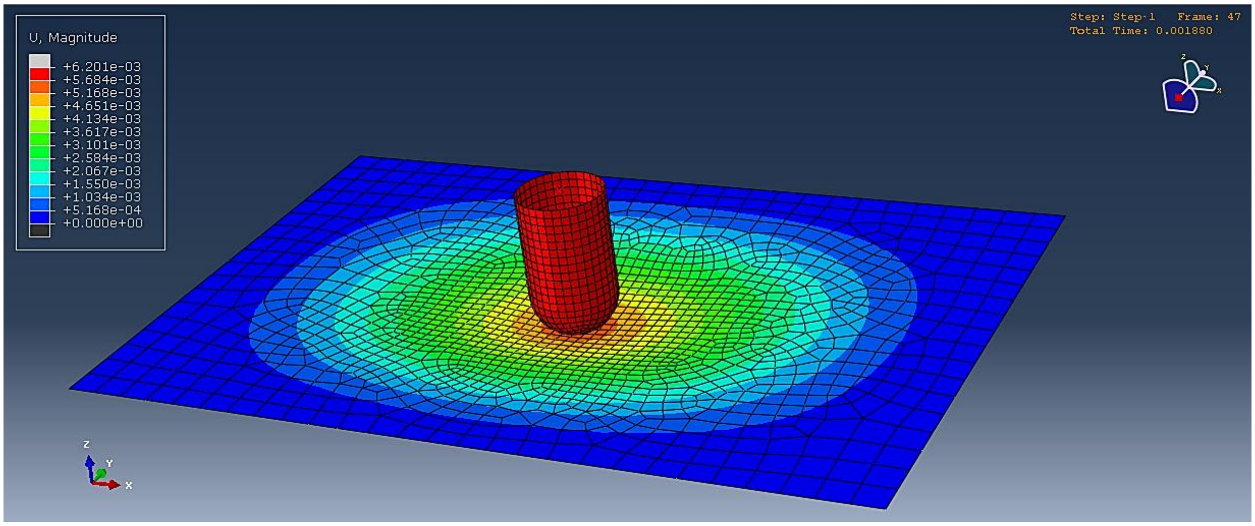


Figure 28. Displacement contour for level 3 impact (legend unit in m)

Figure 29 presents the contour of von Mises stress for the layer 1 of the composite plate for the case of level 3 impact. The impactor geometry is hidden in this contour for the better observation of the stress intensity. It can be seen that the center of composite plate receives the largest value of stress among other locations. It is because of the fact that the highest value of impact energy is applied at the center of the plate. The maximum value of von Mises stress is 9.72×10^8 Pa on the center of composite plate. The farther regions from the plate center have a reduced value of von Mises stress which is lower than the values at the edges of plate which are the constraints.

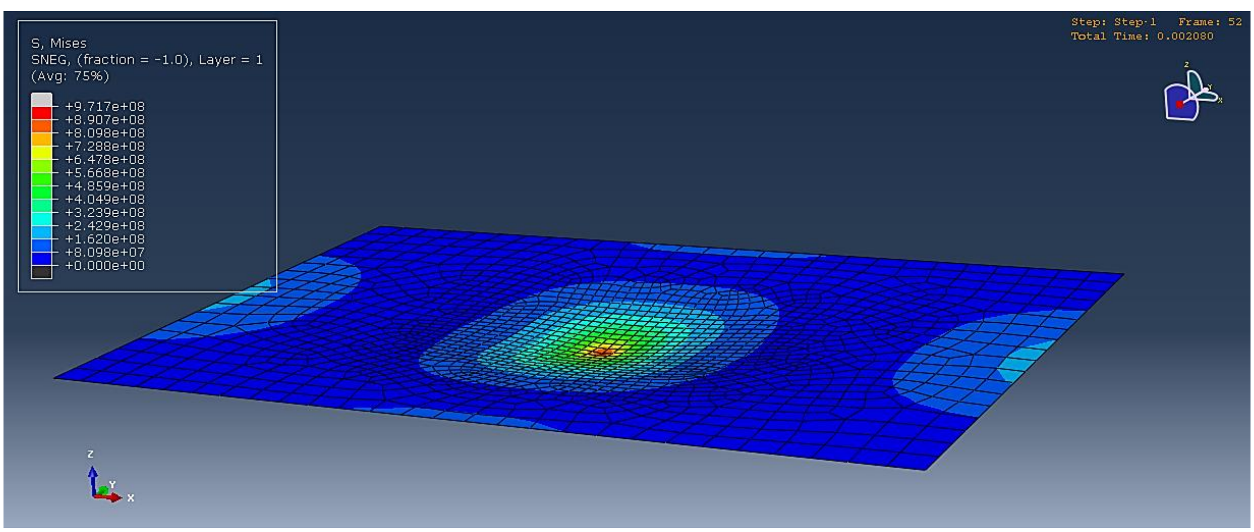


Figure 29. Mises stress for level 3 impact (legend in Pa)

Figures 30 and 31 show the Hashin criterion contours for tensile and compressive damage of the first layer of composite plate for the level 3 impact. It should be mentioned that if the value of Hashin criterion is less than 1, there will be no failure on the materials under impact loading. With respect to the maximum value of Hashin criterion for tensile damage presented in Figure 24, the maximum Hashin criterion is 0.53 at the composite plate center. Since this value is less than 1, no failure occurs on the composite plate due to the impact loading on the first layer of composite.

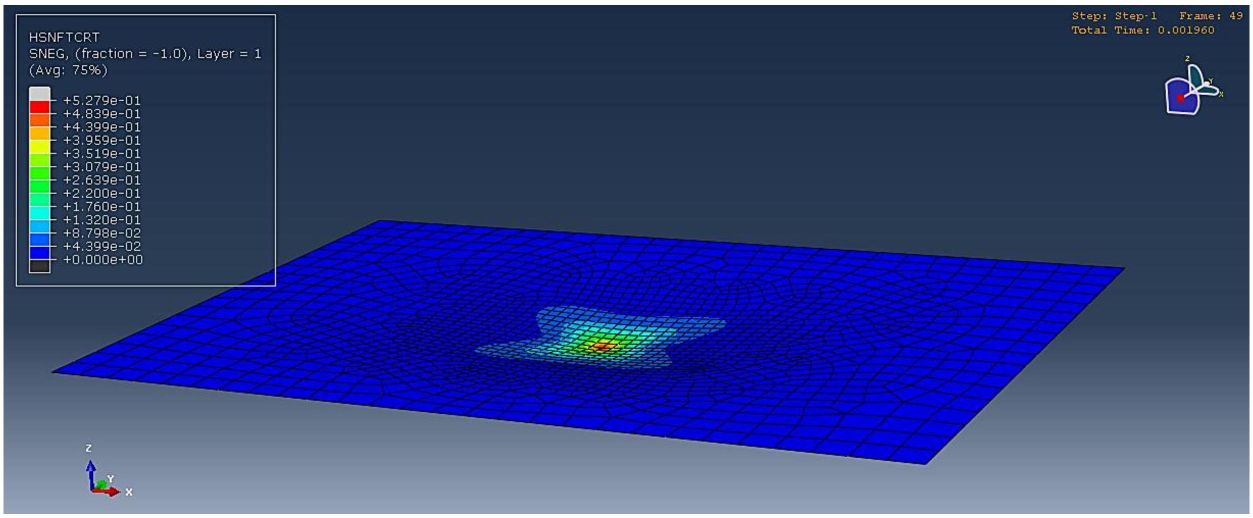


Figure 30. Hashin fiber tensile damage initiation criterion for level 3 impact

For the case of Hashin criterion for compressive damage given in Figure 31, the maximum value of Hashin criterion is 1.83 at the regions of constraints. Therefore, failure will be expected for these locations as the criterion is higher than 1. It means the first layer of composite will be damaged at its edges by the level 3 impact loading.

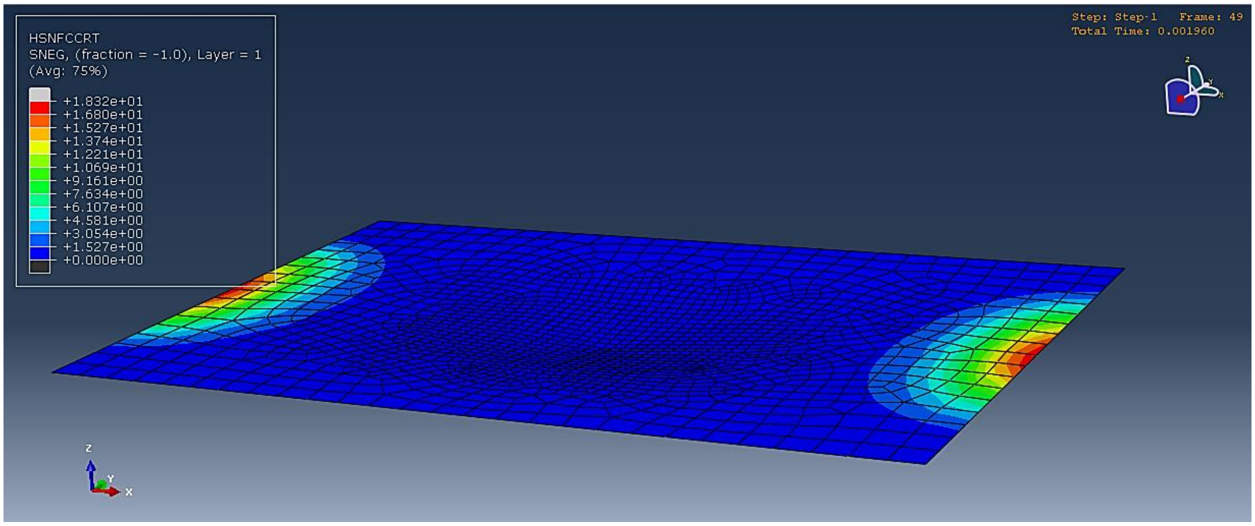


Figure 31. Hashin fiber compressive damage initiation criterion for level 3 impact

4.3.2 Plots

The evolution of impact energy by the impactor on plate plot is plotted in Figure 32 for the impact level 3. The calculated energy from the impactor falling from an elevation of 1 m as the level 3 is 18.16 J. As it is shown in Figure 32, the contact time is again around 4 ms; 2 ms takes to reach the peak impact energy and another 2 ms for the dissipation of this energy. The maximum value of impact energy is around 17.8 J which is a bit less than the expected value of 18.16 J.

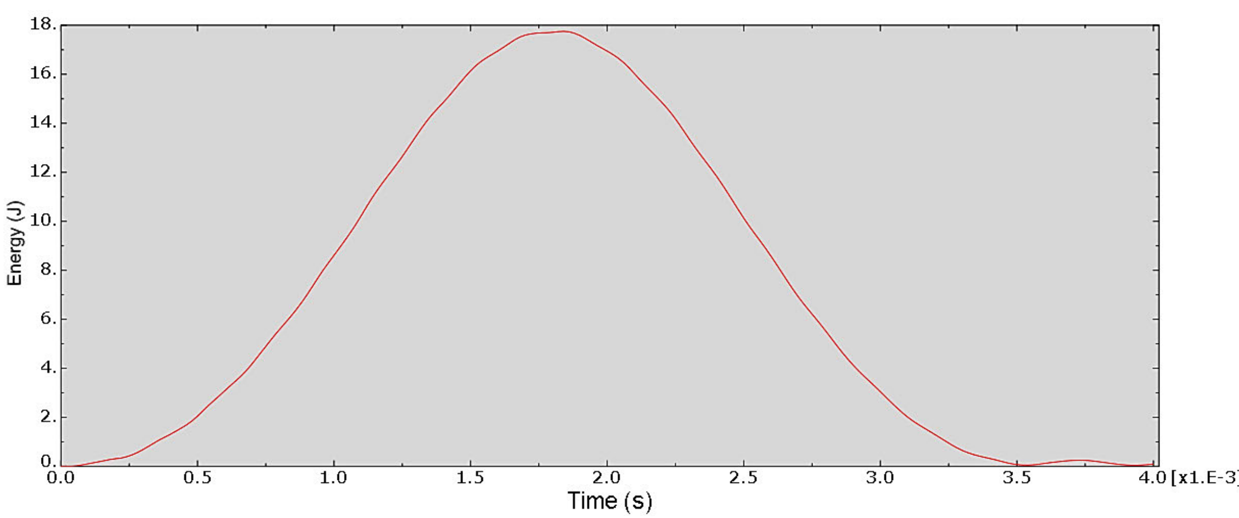


Figure 32. Progress of impact energy for level 3

Figure 32 presents the displacement plot of the composite plate at its center point, the contact point of the impactor and the plate. As it is clear, the peak value of this plot is at the time of around 2 ms which is the time of maximum impact energy. The value of maximum deflection for the level 3 impact from this plot is around 6.2 mm. The plate center backs to the zero deflection at the time of around 3.75 ms and then gets another cycle of fluctuation.

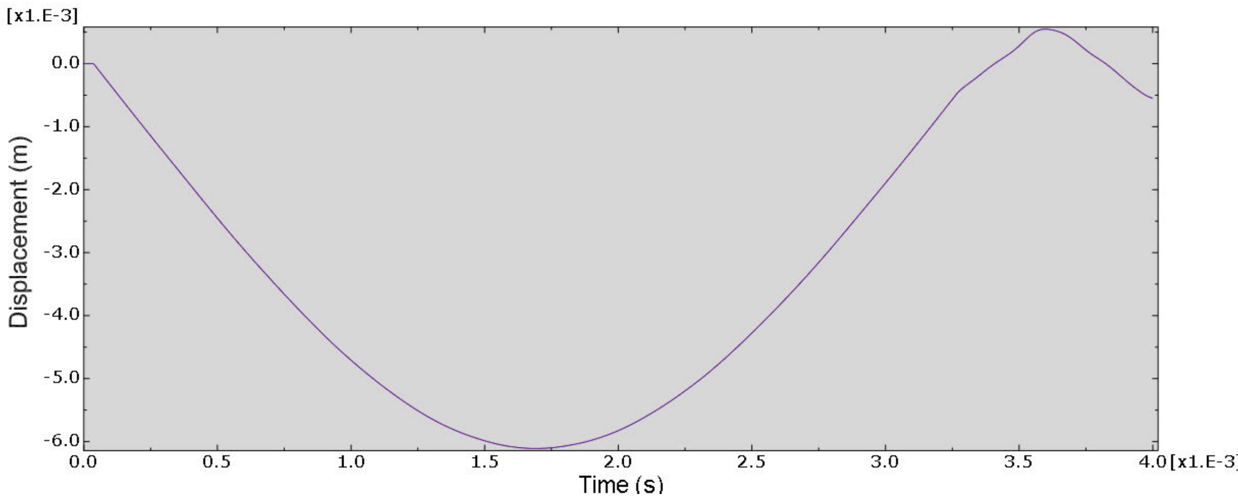


Figure 33. Deflection of the center of composite plate for level 3 impact

4.3.3 Validation

This section is allocated to the comparison of the obtained results for the level 3 impact from ABAQUS and experimental data reported by Zouggar et al. (2016). It is performed for the maximum values of the maximum impact energy and deflection of the center of composite plate. From the experimental data for the level 3 impact, the maximum impact energy and deflection of the plate center are 18.12 J and 7 mm, respectively. The corresponding values from ABAQUS simulation are 17.8 J and 6.2 mm, respectively. Therefore, these results generate a percentage error of 1.8% for the maximum impact energy and 11.4% for the maximum deflection of the plate center.

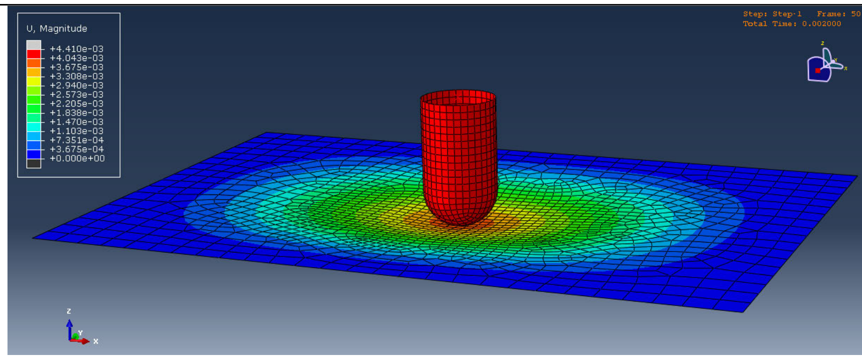
Table 6. Validation of ABAQUS results for level 3 impact

Parameter	Experimental value	Simulation value	Percentage error
Impact energy	18.12 J	17.8 J	1.8 %
Maximum deflection	7 mm	6.2 mm	11.4 %

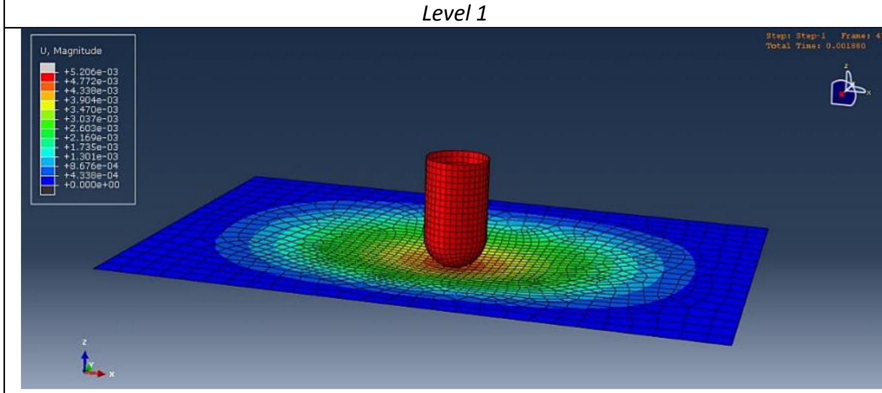
4.4 Results comparison for different energy levels

The obtained results for the impact simulation of the composite plate with different impact energy levels are compared in this section. It should be mentioned again that the ABAQUS simulations were performed for three drop heights; 0.5 m (level 1), 0.75 m (level 2) and 1 m (level 3) to generate the impact energy of 9 J, 13.6 J and 18.16 J during the impact, respectively.

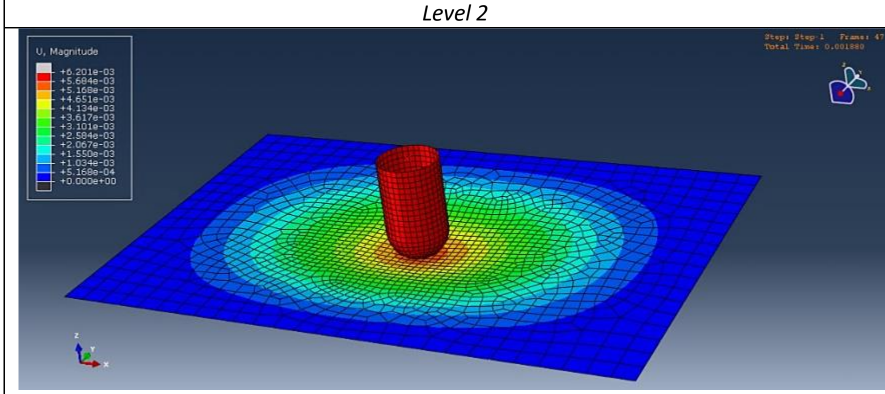
The obtained displacement contours are presented in Figure 35 for a better comparison. It can be seen that the deflection of the plate center increases by the increase of the energy level. It is due to the fact that the higher energy levels are generated by the higher impact drop height, higher velocity and hence higher impact energy. The maximum deflection of the plate center at the plate center are 4.41 mm, 5.2 mm and 6.2 mm for the impact energy levels of 1, 2 and 3, respectively.



Level 1



Level 2



Level 3

Figure 34. Obtained displacement contours for different impact energy levels

Figure 35 shows the contours for von Mises stress at three levels of impact energy. As it is expected, the higher impact energy level imposes the higher stress on the plate because of generating the larger impact energy. The amounts of maximum von Mises stress at the center of plate are 6.72×10^8 Pa, 8.375×10^8 Pa and 9.72×10^8 Pa for the impact energy of levels 1, 2 and 3, respectively.

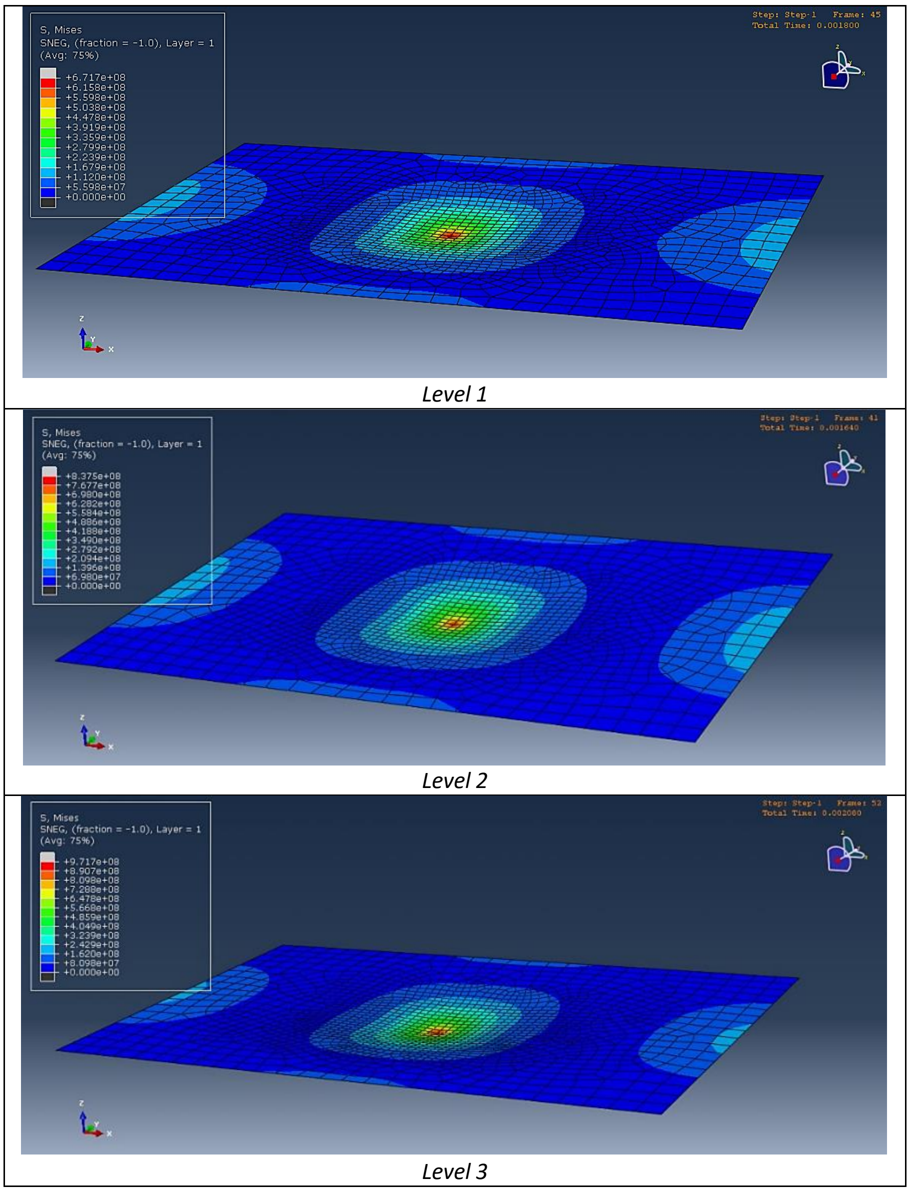


Figure 35. Obtained von Mises contours for different impact energy levels

The Hashin fiber tensile damage initiation criterion contours for different impact energy levels are given in Figure 36. It can be seen that as the plate experiences a higher impact energy level, the amount of Hashin damage increases. It is because of the amount of the impact energy which is applied on the plate which increases by increasing the drop height and hence the impact velocity. The Hashin criterion is around 0.25, 0.39 and 0.53 for the impact energy levels of 1, 2 and 3, respectively. Since all of these amounts are less than 1, no failure happens on the composite plate after the impact loading.

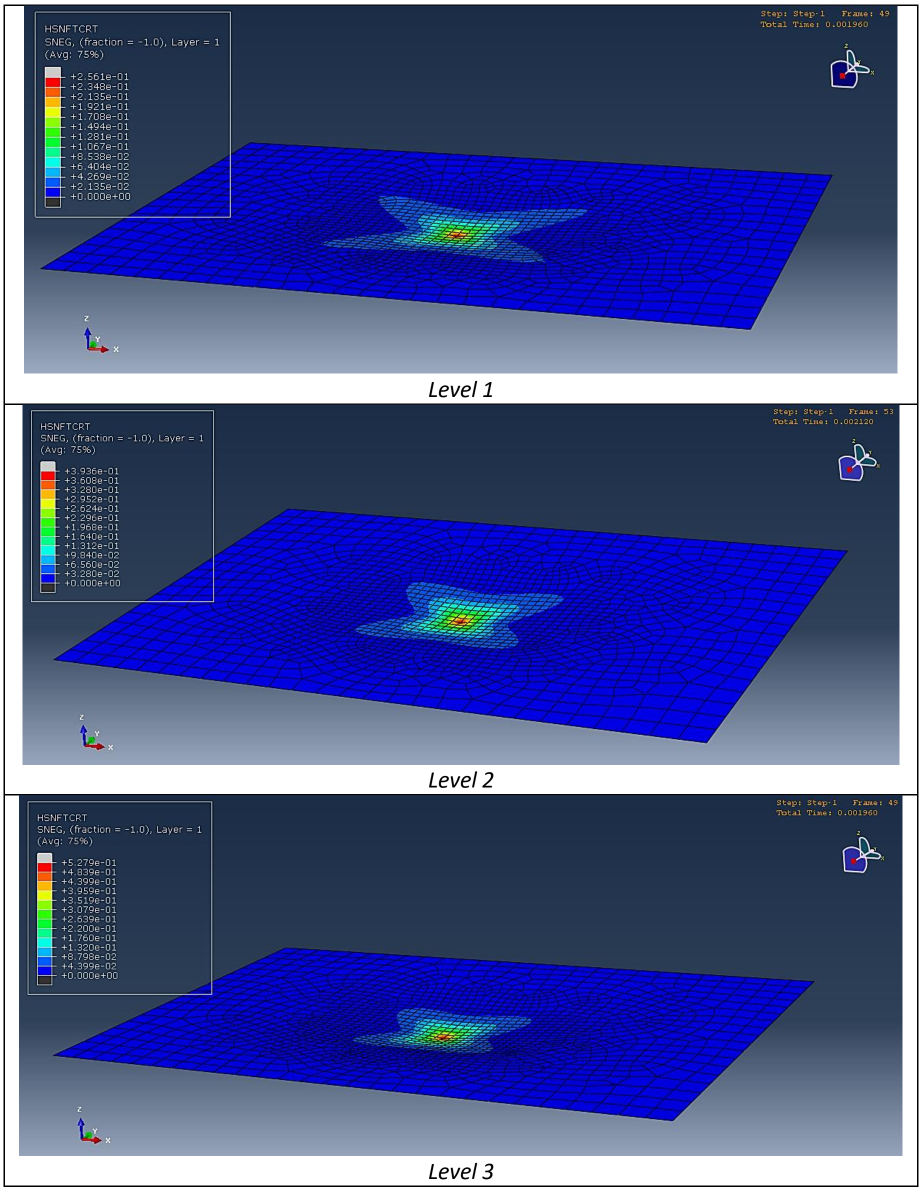


Figure 36. Obtained Hashin fiber tensile damage initiation criterion contours for different impact energy levels

The obtained plots from ABAQUS simulation for the evolution of impact energy at different levels are presented in Figure 37. As it is obvious, the maximum amount of impact energy increases with the increase of impact level. It is due to the fact that the drop height of the impactor on the composite plate increases at higher levels which generates a higher impact energy during the contact. The values of the impact energy are 8.95 J, 13.4 J and 17.8 J for the impact energy levels of 1, 2 and 3, respectively. Another point which can be seen in these plots is the cycle time of a full contact. For the level 1 impact, this period is about 4 ms, but it decreases for the higher energy levels. It can be said that the contact period for energy levels of 2 and 3 are 3.75 ms and 3.5 ms, respectively. It can be due to the increase of drop height of the impactor and a faster response of the composite plate after the impact.

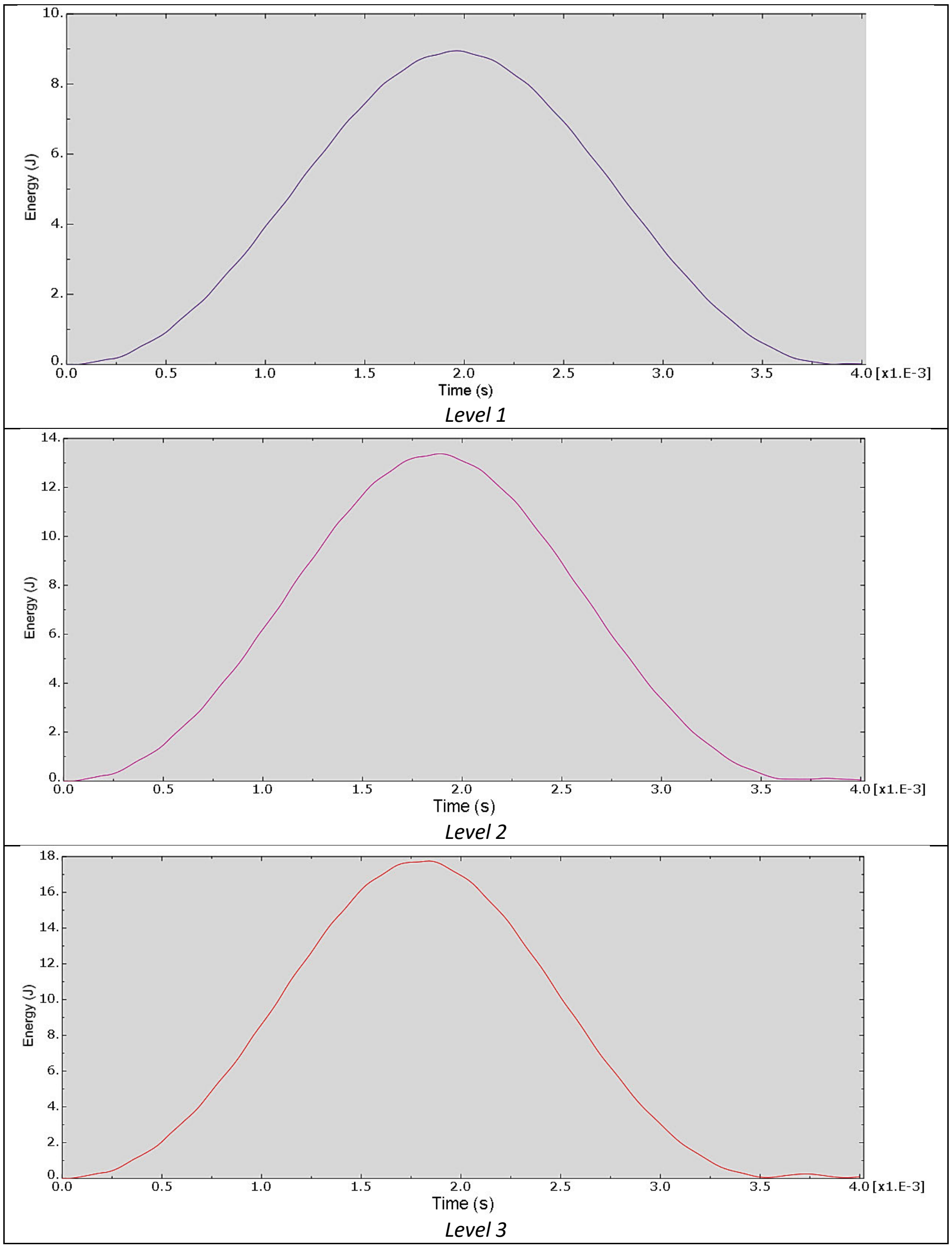
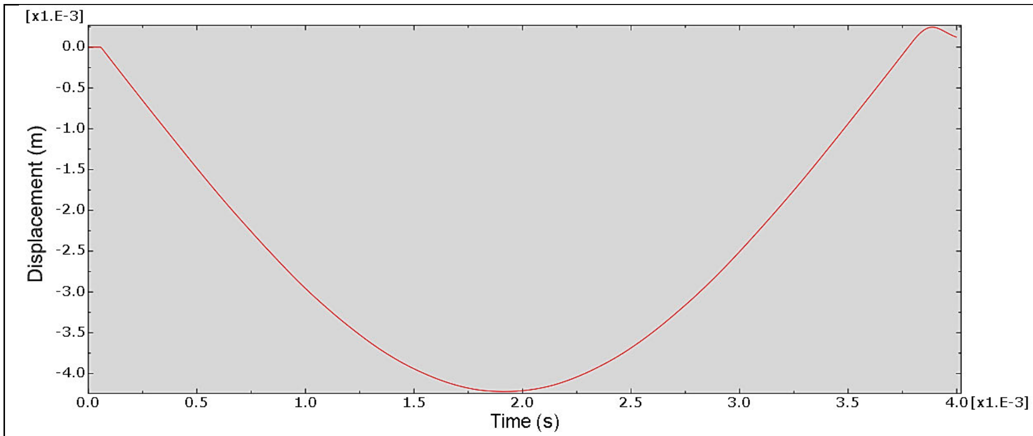
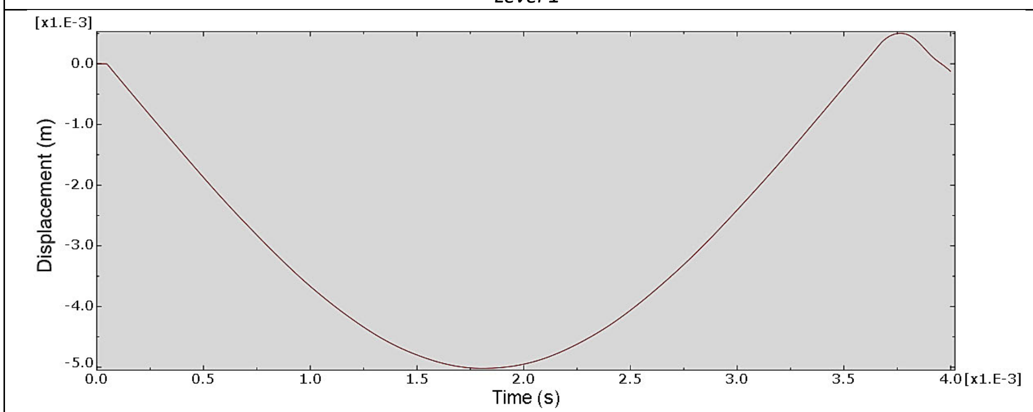


Figure 37. Obtained plots for progress of impact energy at different levels

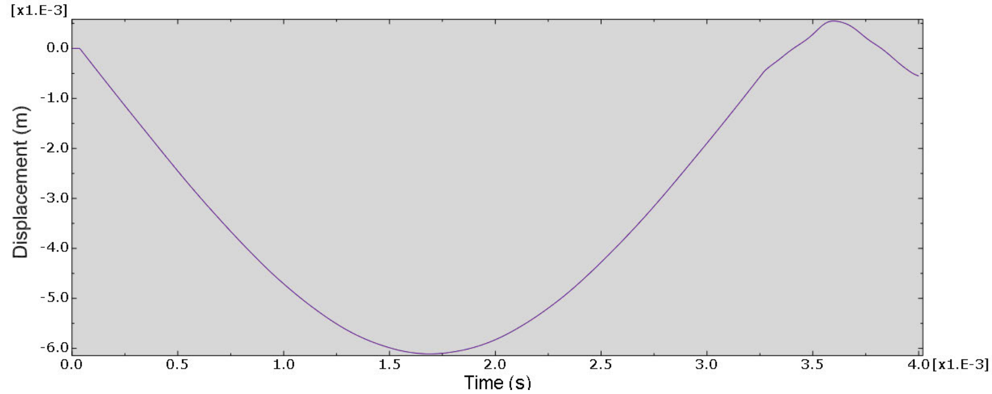
Figure 38 shows the obtained plots for displacement of the composite plate center for different impact energy levels during the period of impact. It is seen that the amount of displacement of the plate center increases with the increase of the impact level. It is obvious that the higher level of impact energy imposes a higher impact load on the plate which results in a higher deflection of its center. The values of center deflection for the impact energy of 1, 2 and 3 are 4.4 mm, 5.2 mm and 6.2 mm, respectively. It can be also seen that the contact period decreases by increase of the impact energy level due to the reason that was explained for the impact energy evolution plots.



Level 1



Level 2



Level 3

Figure 38. Obtained plots for displacement of the plate center at different impact levels

Chapter 5. Conclusions

The simulation of impact on a model composite plate was performed in this project using the ABAQUS software and the simulation results were validated with the experimental data obtained from the literature. The ABAQUS Explicit method with dynamic explicit solver which is suitable for the impact problems was selected for simulation. The composite model was from the type of S glass/Polyester composite laminate plate with eight plies and stacking sequence of $[0/0/0/90]_s$. The produced geometry of composite plate as lamina was modelled with anisotropic elasticity and the Hashin criterion was used in order to predict damage and failure behavior of the composite plate. Three different levels of impact energy were selected by choosing different drop heights of the impactor on the composite plate and hence difference impact velocities. Based on the obtained results, it can be concluded that:

- The higher drop height of the impactor will generate a higher impact energy on the composite plate
- The higher impact energy on the composite plate leads to formation of a higher value of von Mises stress
- The higher impact energy on the composite plate leads to a larger deflection and displacement of the composite plate at the location of impact
- The maximum deflection of the plate happens at the time of maximum impact energy
- The value of Hashin damage criterion for the composite plate increases with the increase of the impact energy level
- The period of impact on the composite plate decreases with the increase of the impact energy level
- Based on the calculated percentage error for the simulation results and the experimental data, ABAQUS can simulate the impact phenomenon on the composite materials with a reasonable level of accuracy.

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