Controlled impact tests on composite materials: Damage development and energy analysis

by

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Abstract

In addition to their many advantages, one of the disadvantages of composite materials is that they can have low impact resistance due to their brittle nature. Recently there has been growing interest in the use of shape memory alloys (SMAs) to reinforce composites subjected to impact. The present study has investigated the impact resistance of glass/epoxy woven fabric specimens, with different number of woven layers, with and without additional reinforcing SMA wires. The specimens were tested using a specially designed impact rig mounted on a servo-hydraulic testing machine; the impact rig provides a constant velocity for the impact event and makes it possible to produce three kinds of impact experiments - multiple, single and partial penetration impact tests. In addition, a video camera is used to record damage viewed from the exit surface of the impact specimens. Eight, four and two-layer specimens were investigated, and two-layer woven fabric specimens with SMA wires showed the best improvement in impact resistance from all the specimens tested.

The development of damage within the two-layer composites was investigated macroscopically and microscopically. Damage was found in the form of matrix cracks and delamination even for low impact loads (and displacements). With regard to specimens containing SMA wires, as a consequence of the superelasticity of the wires not all the embedded SMA wires failed within the impact area of a specimen, even after the specimen was completely penetrated.
An energy analysis has been performed on all the results of the control impact testing, to investigate an empirical formula suggested recently in the literature. The results are in reasonable agreement with the empirical formula suggested, although a more appropriate expression linking the impact energy ($U_{imp}$), the absorbed energy ($U_{abs}$) and the penetration energy ($U_p$) is

$$\frac{U_{abs}}{U_p} = \left( \frac{U_{imp}}{U_p} \right)^\alpha$$

where $\alpha$ lies between 1.5 and 2.

This work suggests that superelastic SMA wires can improve the impact resistance of specimens particularly when through-thickness penetration of the specimens occurs and the large energy absorbing characteristics of the wires are used when the volume of the SMA wires is high.

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Composite materials have been widely used in industry over the past decades due to their many properties such as high strength, stiffness, corrosion resistance, improved fatigue properties and light weight compared to metals. Despite these various advantages, one of the most important disadvantages of composite materials is that they have weak impact damage tolerance. Impact damage is not generally considered to be a threat in metal structures because of the large amounts of energy that can be absorbed through plastic deformation. By contrast, the inherently brittle nature of polymer matrix composites means that damage which is barely visible in a composite component can still pose a significant threat, either through an immediate reduction in mechanical properties (especially in compression strength after impact) or through damage growth during fatigue loading. Composites have a limited ability to undergo plastic deformation; therefore the energy absorbed during impact forms large areas of fracture. Consequently, new materials and processes are continually being sought to improve the impact tolerance of composite materials. An important candidate currently, is the use of shape-memory alloy (SMA) wires to absorb impact energy during the impact event.

It is well known that shape memory alloys show promising applications in many areas of engineering. One property which is of importance in designing SMA-reinforced composites for improved impact resistance is called superelasticity (or pseudoelasticity). For certain types of SMA materials, application of a stress produces
a reversible phase change from an austenitic to a martensitic phase (stress-induced martensite) that allows large strains to be developed, up to about 8%. Extension of the material to higher strains produces plastic deformation and large amounts of energy absorbed prior to failure. Relaxation of the material reverses the transformation, but with the dissipation of absorbed energy. It is this feature of SMA wires, the ability of superelastic wires to dissipate energy, which is most likely to provide a practical method of improving impact resistance when the wires are embedded in composite materials.

Part of the aim of this project is to elucidate the contribution of the SMA wires to improving impact resistance. In doing so, the project makes use of in situ observations of damage development in transparent specimens, using a digital video camera mounted in a specially constructed impact rig mounted on a servo-hydraulic testing machine. The study applies the technique not only to shape-memory alloy reinforced composites, but also to composites without any secondary reinforcement. Another aim of the work is to characterize the growth of damage in the woven fabric specimens macroscopically and microscopically. Finally, it is also the aim of the work to compare the experimental results with suggested relationships in the literature for energy absorption during an impact event.

The structure of the thesis is as follows, the next chapter (Chapter 2) is a brief literature review of the architecture of various types of composite materials, types of impact tests and damage development of composite materials without SMA wires. It also gives relevant background on SMA wires, SMA composites and previous work in this field. Chapter 3 describes the methodology used to prepare and carry out the experimental work as well as the material used and the manufacturing procedure for the laminates. Chapter 4 describes the material properties of the SMA and copper wires and also the predicted and experimental values of the Young's modulus of the fabricated composites.

 Chapters 5 and 6 show the impact test results of the eight- and four-layer (Chapter 5) and two-layer (Chapter 6) woven fabric composites, with and without copper or SMA wires. The following chapter (Chapter 7) presents the analysis of the energies derived
from the impact tests which also helps to identify any differences between specimens with and without copper or SMA wires. Chapters 8 and 9 describe the macroscopic and microscopic analysis of the damage developed in two-layer woven fabric specimens with and without copper or SMA wires.

Chapter 10 presents a limited study on the controlled impact of cross-ply glass/epoxy laminates. The chapter describes the impact test results and the energy analysis for the cross-ply specimens. Finally, the last chapter (Chapter 11) contains concluding remarks and suggested future work based on this work.
Chapter 2

Literature Review

2.1 Introduction

The present study is mainly concerned with the damage development and energy absorption of specimens with and without shape-memory alloy (SMA) wires under impact tests. This literature review consists of a brief outline of different architectures of composite materials such as unidirectional, cross-ply, woven fabric and other textile composites and covers the background of impact tests and failure mechanism of these different kinds of composite materials. In addition, methods of reducing the impact damage are also considered. It continues by discussing the properties of shape-memory alloys (SMA) and the use of SMA wires in composite materials.

2.2 Architecture

2.2.1 Laminates based on unidirectional plies

Composite materials contain a wide range of materials based on metals, ceramics or polymers reinforced with fibres or particles. Polymer matrix composites, the subject of this work, offer a very wide range of properties including very high stiffness and strength. They can be made from different kinds of reinforcement such as unidirectional, cross-ply and angle-ply laminates and textile reinforcements i.e. woven (two- and three-dimensional), knitted, non-crimp and braided fabrics. Composite materials have been tested in different types of mechanical tests, such as tensile tests,
three-point or four point tests, and impact tests. The specimens used for this study are made from two-dimensional woven E-glass and cross-ply E-glass reinforcement with epoxy resin and therefore more attention will be given to these types of fibre architecture.

A unidirectional composite is a composite where all the fibres of the lamina are aligned parallel to one another. Unidirectional laminates are orthotropic; they have three mutually perpendicular planes of symmetry. They are not homogeneous and have low interlaminar strength and poor toughness when undergoing an out-of-plane loading. Figure 2.1 shows a schematic image of a unidirectional lamina of a composite material.

![Figure 2.1 - Schematic unidirectional lamina of a composite material [Hull and Clyne, 1996].](image)

The fibres provide the strength and stiffness of a composite, therefore the higher the fibre fraction the higher the strength and stiffness which are greatest in the direction parallel to the fibres. Hence unidirectional fibre composites offer high strength and stiffness in the directions parallel to the fibres, but offer very low strength and stiffness in the direction perpendicular to the fibres.

Laminates can be created by combining plies in two or more directions. Cross-ply laminates have only 0° and 90° plies and angle-ply laminates have plies at any angle. They are less anisotropic than the unidirectional lamina. Figure 2.2(a) shows a typical cross-ply lay-up and Figure 2.2(b) shows an example of an angle-ply lay-up.
The simplest visible damage which can occur in cross-ply laminates and which will be seen in the work within this thesis, is matrix cracking damage. For example, Garrett and Bailey (1977) tested cross-ply glass reinforced polyester specimens with different ply thicknesses (0.3mm-4mm) in tension, at different strain rates at a strain range of 0.2% to 1.8%. The strain was measured by strain gauges which were placed on the specimens. They found multiple matrix cracks in the 90° ply, perpendicular to the tension load, after a strain of 0.4% to 0.5% which was considered as the crack initiation strain. No delamination was found between the 0° and 90° plies. They also noticed that at saturation the spacing between these cracks depends on the thickness of the specimen; the higher the applied stress and the smaller the 90° ply thickness, the smaller is the average crack spacing. These findings were examined in more detailed by Parvizi and Bailey (1978) as part of a wider investigation into cracking mechanisms in these systems [Parvizi et al, 1978]. Parvizi et al (1978) tested cross-ply E-glass reinforced epoxy specimens with different ply thicknesses (0.1mm-4mm).

They agreed with the Garrett and Bailey (1977) results and furthermore in the investigation they observed that cracking was suppressed in the inner 90° plies at small ply thicknesses, whereas for thicker 90° plies uniform cracking in the inner 90° plies was found.

Figure 2.2 – A sketch of a typical (a) cross-ply laminate with a lay-up of (0/90/0/0/90/0) and (b) of an angle-ply laminate with a lay-up of (0/60/-60/60/60/0) [Hull and Clyne, 1996].
2.2.2 Laminates based on woven fabrics

Woven fabric is widely used in industry in the manufacture of glass, carbon and aramid fibre composites. Such fibres can be classified according to their structure or weave, which is to the manner in which warp and weft cross each other in the loom. Two-dimensional woven fabric is often made of two sets of equally orthogonal yarns or tows. Warp tows are the tows aligned in the weave direction, whereas weft or fill tows are the ones aligned across the weave direction. In some areas in a tow, a curvature exits to allow it to pass above or below another tow orientated in the opposing orthogonal direction; these areas are called crimps [Hull and Clyne, 1996].

There are three fundamental weaves: plain, twill and satin. In plain weave the weft passes over alternate warp threads requiring two harnesses (loops) only. Twill is made by interlacing weft threads with two or four warp threads moving a step to right or left with an offset “step” between rows forming a diagonal design. Satin weave is made by four or more weft yarns floating over a warp yarn or vice versa.

A woven cloth can be characterised by a number of parameters such as its weight and its thickness (estimated under a specific compressive load). The tows are described by the weight in grams of 1000m of the tow. This is the tex value of the tow. The number of warp tows and the number of weft tows per unit length are called ends and picks respectively. In order for a cloth to be balanced the number of ends must be equal to the number of picks. The imbalance of a fabric affects the final laminate properties, for example when the number of ends is double than the number of picks the longitudinal stiffness is approximately double in that direction [Hull and Clyne, 1996]. By using different kinds of fibres in the warp and weft tows, the laminate properties change and this kind of fabric is called a hybrid. It might also have different kinds of fibre in the same orthogonal direction or even co-mingled into the same yarn. Woven fabric can be identified by the repeating pattern created by crimps and they can be classified by notation developed by Chou and Ishikawa (1989) which defines whether a cloth is plain, twill or satin.
The different weave orientations give different characteristics in a fabric. An eight harness woven cloth is stiffer than a plain weave cloth with the same fibre volume fraction, because it has a lower number of crimps present. Plain weave cloth has a higher impact resistance due to the high density of crimp areas that localise the impact damage by arresting the cracking at the warp/weft crossover points. Furthermore, plain weave laminates tend to have a higher volume fraction than an eight harnesses laminate with the same number of layers, due to periodicity of the crimp areas that nest together more tightly [Belmonte, 2002]. Figures 2.3(a)-2.3(c) show schematics of plain weave, twill weave and of eight-harness satin weave, respectively. The woven cloth used in this work is plain weave.

![Figure 2.3](image_url)

Figure 2.3 – Woven fabric styles: (a) plain weave (b) twill weave (c) eight-harness weave [Belmonte, 2002].

### 2.3 Impact of composite materials without SMA wires

#### 2.3.1 Impact tests

The impact test is a test of the ability of a specimen to resist high-rate loading and to determine the energy absorbed by the specimen during impact. There are two types of impact tests, low velocity i.e. simulating drop of a tool, and high velocity (ballistic) i.e. simulating small arm fire. Richardson and Wisheart (1996) provide a definition of low and high velocity impact. Low velocity impact can be defined as a quasi-static impact with velocity between 1ms\(^{-1}\) and 10ms\(^{-1}\). High velocity impact is the impact with velocity above 10ms\(^{-1}\). During a high velocity impact the target has no time to
respond and the damage is localised, whereas in low impact velocity the damage area is extended. Figure 2.4 shows a schematic drawing of low and high velocity impact.

![Figure 2.4 - Schematic drawing of (a) low velocity impact and (b) high velocity impact [Bibo and Hogg, 1996]](image)

An example of high velocity impact is the gas-gun systems which produce high velocities with small impactors. In a gas-gun system compressed air with high pressure is released from an accumulator, travels through a gun barrel and impacts the specimen [Abrate, 1991]. Some examples of low impact velocity test are Charpy and Izod impact test, Hopkinson-type pressure bar and drop weight tests. In a Charpy test the beam specimen is supported at two ends and it is hit by a pendulum at the midspan. In an Izod test the beam specimen is held at the one end and it is hit by a pendulum at the free end [Agarwal and Broutman, 1990]. The fracture of composite materials is complex and Charpy and Izod impact tests cannot give the data needed concerning the impact damage and energy absorption of the composites.

The drop weight impact test is most commonly used to study the impact behaviour of composites and to record the load history. In a drop weight impact test the specimen is clamped and a known weight is dropped from a known distance. The required impact velocity can be achieved by changing the distance of the impactor from the specimen. From a drop weight impact test the load-time response is given [Dorey, 1988]. Figure 2.5 shows a schematic load-time response during a drop weight impact test. The response is separated into two regions; its fracture initiation and fracture propagation regions. In the fracture initiation region, impact energy is absorbed by the specimen as
the load increases, and only microscopic damage is formed (e.g. matrix cracks and delamination). At the end of the initiation phase, the peak load is reached and the fracture propagation region begins with initiation of penetration of the specimen. The specimen continues to absorb impact energy at lower loads. The total energy needed to penetrate the specimen is the sum of the impact energy in the fracture initiation region \( (E_i, \text{ as indicated on Figure } 2.5) \) and the impact energy in the fracture propagation region \( (E_p, \text{ as indicated on Figure } 2.5) \) [Agarwal et al, 2006]. The load-time response recorded from the test is integrated to give the energy absorbed with respect to time [Agarwal and Broutman, 1990; Instron.com].

\[
E = \int P \cdot v \, dt
\]

\[
E_i = E_i + E_p
\]

Figure 2.5 – Schematic load-time response during drop weight impact test [Agarwal et al, 2006].

There have been many papers published using the drop weight impact test. For example, Winkel and Adams (1985) tested six different glass systems and architectures with epoxy resin, with different number of plies. They tested cross-ply and woven plates of graphite, Kevlar-49 and E-glass. Figure 2.6 shows a typical load-time and energy-time response of an E-glass/epoxy composite. As mentioned above, the energy curve is derived by the integration of the load-time curve. They concluded that the results from an instrumented drop weight impact test depend on specimen thickness which will be discussed further in section 2.3.3. The difference in impact performance between the woven fabric composites and the cross-ply composites was about the same for both graphite/epoxy composites and Kevlar-epoxy (with the cross-
ply absorbing more energy), but with much larger differences for the E-glass/epoxy systems.

Figure 2.6 – Load-time and energy-time response of a cross-ply E-glass/epoxy composite
[Winkel and Adams, 1985].

Belingardi and Vadori (2002) tested three different stacking sequence of glass fibre/epoxy material, with both woven and cross-ply lay up in drop weight impact tests. Two threshold values of force were identified: threshold damage load and peak load. Threshold damage load is initiated when the first material damage occurs and the peak load is the maximum load recorded during the test, which occurs just before the first macroscopic through thickness crack damage (initiation of penetration), after both loads can lead to a sudden drop of load. These values stayed constant with the change of impact energy, if the impact energy is large enough to produce these threshold loads, and were similar between the unidirectional and woven materials.

Atas and Sayman (2008) tested four-layer plain weave E-glass fabric composite plates with epoxy resin with an instrumented drop weight impact testing machine. The impactor used was hemispherical with a 12.5mm diameter. The height and mass of the impactor was varied so that different range of incident impact energies was achieved. Load-displacement responses of the impact tests were produced from the load histories given by the drop weight machine. They found two types of load-displacement curves, "closed type" and "open type". The close type is when the impactor rebounds and open type is when the impactor penetrates the specimen.
Figure 2.7 shows four graphs of load-displacement for different impact energies. At low impact energies, a close type load-displacement curve occurs (Figure 2.7(a)). The impact load cause only minor damage on the specimen. The first major damage took place at higher impact energies, at around 8mm, which reduced the stiffness of the specimen (Figure 2.7(b)) and the hysteresis loop formed from the loading-unloading cycle increased implying significant damage (Figure 2.7(c)). In addition, after the peak load the load dropped suddenly. As the impact energies increased the load-displacement curves became open. In Figure 2.7(d), the curve of specimen named ‘13’ shows an almost full penetration and the curve of the specimen named ‘17’ shows a complete penetration. Atas and Sayman (2008) also related the hysteresis loops to damage formed on the composites and this will be discussed in the next section, 2.3.2.

![Figure 2.7](image)

**Figure 2.7 – Load-displacement responses of glass woven fabric specimens for varied impact energies [Atas and Sayman, 2008].**

Kim and Sham (2000) compared the impact response of woven and cross-ply carbon/epoxy laminates. Figure 2.8 shows three typical load-displacement responses of carbon fibres/epoxy composites with woven fabrics, 16-layer cross-plies and 18-layer cross-ply laminates, respectively. On the load-displacement response of the cross-ply composite, the threshold damage load (P_t) and the peak load (P_m) can be identified. On the other hand, the woven fabric composites did not experience any load drops or changes in the slope until the peak load was reached. After the peak load
in a cross-ply composite response, the load drops rapidly to zero. On a woven composite response, though, the load dropped gradually to zero after showing an almost constant load at a high value of load, for few millimetres. The woven fabric laminate was completely fractured at a higher displacement than the cross-ply laminates. There is a conflict about the sudden drop of loads in the woven fabric specimens. Some researchers found no sudden drop of load in impact testing of woven fabric laminates [e.g. Chou et al, 1992; Siow and Shim, 1998]. Kim and Sham (2000) also investigated the damage area on woven and cross-ply laminates and this will be discussed in the next section 2.3.2.

![Figure 2.8](image)

**Figure 2.8** – Typical load-displacement responses of carbon fibre/epoxy composites with (a) woven fabrics, (b) 16-layers cross-ply laminates and (c) 18-layer cross-ply laminates [Kim and Sham, 2000].

### 2.3.2 Damage development

#### 2.3.2.1 Introduction

In general, the damage accumulated during impact tests is similar in all types of polymer matrix composite materials and can be separated into different categories: intralaminar matrix cracking, longitudinal matrix splitting, delamination, fibre/matrix debonding, fibre pull-out and fibre fracture [Richardson and Wisheart, 1996; Cantwell and Morton, 1991; Hull and Shi, 1993; Abrate, 1994]. Figure 2.9 shows the three main categories of damage in a composite material.
Matrix cracking damage is the first damage type to occur in composites in impact tests. The cracks are formed due to the property mismatching between fibres and matrix. The type of the matrix cracks formed, such as angle or shear cracks, 90° or bending cracks, depends on the overall structure of the specimen under testing. Shear cracks start under the edge of the impactor due to transverse shear stress and the cracks are oriented at an angle around 45°. Bending cracks are vertical cracks located in the lower ply in the middle of the impact area and are formed due to tensile bending stresses [Richardson and Wisheart, 1996].

A delamination is a crack which runs in the resin-rich area between plies of the same or different fibre orientation. These cracks are produced by interlaminar stresses and are responsible for absorbing a major amount of the fracture energy. They occur after a specific threshold energy of the specimen is reached and only if a matrix crack is present [Richardson and Wisheart, 1996]. Figure 2.10 shows the relationship between matrix cracks in the 90° ply and delaminations at the interface of that ply and the 0° ply. Hull and Shi (1993) reported that major shear matrix cracks are always connected with delaminations, irrespective of the stacking sequence of the specimens. Doxsee et al (1993) studied the growth of delaminations in cross-ply carbon/epoxy laminates subjected to what they called “transverse loads”, but seem to be very low velocity impact tests. They used cross-ply carbon fibres reinforced polymers (CFRP) specimens with and without a started delamination (using aluminium foil) between one pair of 0° and 90° plies. The damage grown was examined by C-scan, optical microscopy and radiography throughout the experiment. They found that the
delaminations grow with increasing impactor displacements and that the energy absorbed for delamination growth was constant with a value of about 600\(\text{J/m}^2\).

Fibre failure occurs later in the impact test usually after delaminations have developed. Fibre failure in the impact layer occurs due to the locally high stresses and on the exit layer due to high bending stresses. When fibre failure reaches a critical point, the impactor is able to pass through the composite causing penetration [Hull and Shi, 1993].

Damage in composites due to impact can be investigated with different techniques depending on the size of the damage and the transparency of the composite. Some of these methods are visual observations, dye enhanced X-radiography, microscopic examinations, ultrasonic techniques, radiology, thermography, acoustic emission and fibre optics. For example, dye enhanced X-radiography and C-scanning reveal delaminations and matrix cracks, but it is difficult to extract three-dimensional information [Hull and Shi, 1993]. For this, it is often necessary to section the specimens. In the following section, some detailed studies on impact damage development will be described.

**2.3.2.2 Impact tests and damage development**

One of the most important parameters in the investigation of impact resistance of the composite specimens is the development of damage on a specimen during an impact
test and the role of damage on the energy absorption. Hull and Shi (1993) reviewed what they termed the "damage tolerance" of composite materials. They defined damage tolerance as the ability of structure to resist the formation of damage caused by certain forms of external load and the ability to sustain further service load. In their investigation they found that damage tolerance is related to the resin toughness. Macroscopically, the formation of impact damage depends on the stiffness of the laminate, its constraints and the geometry of the impactor. Microscopically, the stacking sequence influences the formation of damage. For example, for similar laminates which are quasi-isotropic and symmetric, the internal damage depends on the stacking sequence of the plies. The principal damage modes on composite materials are shear matrix cracks and delaminations. As mentioned above, matrix cracks are connected with delaminations. Matrix cracks are diverted to delaminations when reaching the 0° plies because the cracks are not able to continue propagating transversely when reaching plies with different fibre orientations. More of the delaminations appeared on the interface closer to the exit layer and the number of delaminations decreased as getting closer to the impact layer. The main reason for this is the transverse shear caused by the impact load. The total delamination area showed a near linear relationship with impact and absorbed energies. Cross-section microscopy showed that even though many shear matrix cracks could be found in each ply, only few open up severely and these major shear cracks are responsible for the permanent deformation near the impact centre.

Abrate (1991), in his review, shows that with simple (0/90), cross-ply specimens, under impact, damage develops in the form of a 'peanut-shape' delamination at the interface between layers with different fibre orientations as shown in Figure 2.11(a). This 'peanut-shape' delamination was seen in the angle-ply laminates at the interface between different plies with orientation, as shown in Figure 2.11(b). The major axis orientation of the "peanut" is in the direction of the fibre orientation of the lower ply (closer to the exit layer) of that interface. Split matrix cracks were found on the exit layer of the specimens parallel to the fibres, extending from one edge of the plate to the other, due to tensile stresses caused by bending. Figure 2.12 shows schematic diagrams of the impact area of a cross-ply composite in transverse and longitudinal
views. The figure shows shear cracks in the upper and middle layers and bending cracks in the lower layer.

![Image of shear and bending cracks]

**Figure 2.11** – Delamination patterns in a (a) cross-ply and in an (b) angle-ply laminate after impact [Abrate, 1991].

![Image of matrix cracks and delamination]

**Figure 2.12** – Shear and bending cracks in a cross-ply lamina as it can be seen in (a) a transverse view and (b) a longitudinal view [Richardson and Wisheart 1996].

In addition to tests on laminates fabricated from unidirectional fibres, many impact experiments on woven fabric composite have been carried out in recent years to try to understand their impact behaviour. Ross and Sierakowski (1973) used gas gun impact testing to examine different types of composites plates and compare them with steel filament/epoxy plates. The types of composite plates used were cross-ply and woven glass/epoxy, nylon, ceramics-nylon with glass/epoxy and planar mica particles with nylon matrix plates. They discovered that ply delamination was the main damage type
that absorbed energy. Not able to take a clear photograph, a schematic pattern of the delamination was drawn and this pattern is shown in Figure 2.13. They concluded that the composite plates had a higher critical velocity (the velocity where penetration occurs) than the mild steel plates for a given density. Furthermore, the type of fracture growth on a composite plate depends on the geometrical arrangements of the fibres.

Cantwell and Morton (1989) also used gas gun impact tests to investigate the influence of various impactor masses on carbon fibre reinforced laminates with different stacking sequence. The results show that for a fixed impactor diameter, the mass of the impactor plays important role in the initiation and growth of damage in the composites. They believed that the incident impact energy of a light fast-moving impactor is localised on the point of impact and most of this energy is absorbed in a damage mechanism connected with very high fracture energy called shear-out process.

Zhou and Davies (1994), for example, tested thick (>10mm) circular glass/polyester woven roving specimens of 150mm diameter with low velocity, drop weight impact tests. They also investigated the impact damage of the specimens visually and by using C-scan and optical microscopy. A load drop was visible in the load history graphs indicating the initiation of damage and the impact energy at that point was defined as the threshold energy below which no damage occurs. For the same laminate, the absorbed energy increased as the impact energy of the impactor increased, indicating more damage was induced. For 10mm thick specimens, as the impact energy increased the load drop became deeper and the load took longer to decay. The 25mm thick specimen had a similar response to the 10mm ones, but the
initial load drop took place at a higher load and the plates were stiffer. At low impact energy levels, the two failure modes that were identified by visually investigating the specimens were matrix cracks and surface microbuckling in a form of stress-whitened. At higher impact energy levels, fibre fracture was found and after C-scanning, delamination was also found.

Sutherland and Soares (1999) carried out low-energy drop weight impact tests on woven-roving E-glass/polyester with five and ten layers. They found that even of the lowest impact energy (10J for five-layer and 22.5J for ten-layer woven laminates) damage occurred. The delamination area of the exit layer of the five-layer woven fabric specimen was rectangular and fibre damage was found in the centre of the impact area. In addition, at the centre of the impact area, circular delaminations were found in the mid-plane of the laminate. The damage area of the impact layer was in a shape of a rhombus containing matrix cracks. The damage area of the ten-layer woven fabric specimens follows the same pattern as the five-layer specimens, but the damage was more severe and the authors believed that this was due to some slippage that occurred where the specimens were clamped, at higher impact energies. Figure 2.14 shows a photograph of the impact and exit layer of a penetrated five-layer woven fabric specimen.

Figure 2.14 - A photograph of the impact and exit layer of a penetrated five-layer woven fabric specimen, impacted at an impact energy of 78J [Sutherland and Soares, 1999].
Shyr and Pan (2003) used a drop weight test rig to test three types of E-glass fibre architectures, multiaxial warp-knit blanket, plane woven fabric and nonwoven mat, with a polyester resin matrix. Laminates with seven and thirteen plies were impacted with 3 different impact energies. After impact they observed a rhombus-shape delamination aligned with the warp and the weft direction of the woven fabric laminate. Figure 2.15 shows an image of an impacted seven-layer woven fabric specimen. The damage area is very similar to the damage area of the five-layer woven fabric specimen shown in Figure 2.14 [Sutherland and Soares, 1999]. The interweave yarns formed a crimped surface on the woven fabric which restricted the delamination growth, because the impact energy could not be transferred in the in-plane. Therefore, the delamination area of the woven fabric laminate was smaller than that of the multiaxial warp-knit blanket. The authors noticed, what they called, a butterfly shape delamination area with the major axis parallel with fibre direction. All nonwoven mat specimens were penetrated and had a small delamination area which indicates impact energy cannot be transferred in the in-plane direction by the random and discontinuous fibres of the nonwoven mat specimens. Shyr and Pan (2003) also noticed a sudden drop of load in the load-time response on all the specimen types which, indicates the delamination failure and they calculated that the threshold damage load (the load just before the sudden drop of load) of the thirteen-layer specimen was three times higher than the threshold damage load for the seven-layer specimen for the same type of composites. Looking at the threshold energy (impact energy at the threshold load), they found that it increases by increasing the number of layers. The authors identified the initiation of the penetration to be after the peak load in the load-time response. The failure mode for the thirteen-layer laminates was fibre fracture dominated, whereas for the seven-layer laminates, delamination was more important.

Figure 2.15 – A photograph of an impacted seven-layer woven fabric specimen [Shyr and Pan, 2003].
In section 2.3.1 the experiments done by Atas and Sayman (2008) were described. Furthermore, in their investigation, they related energy to damage formed on the composites. They calculated the absorbed energy of their specimens from the loop area formed in the load-displacement graph (see Figure 2.7) and by using the kinetic energy methods (i.e. initial kinetic energy minus rebound kinetic energy). The difference between the two methods was very small. Impact energy was defined as the kinetic energy of the impactor right before impact took place. They plotted absorbed energy against the impact energy and divided the points into five zones, indicated by letters A-E (Figure 2.16). The dashed line represents the equal energy line where the absorbed energy is equal to the impact energy.

Within zone A, matrix cracks were observed to be the main damage mode whereas fibre fractures also occurred between points A and B (point 3 at the graph) on the exit layer (non-impacted side) of the laminates. Point 3 was also the threshold energy where critical damage initiated (initiation of penetration). In zones B and C, the main damage mode was the bending fracture of fibres and also matrix cracks were formed on the impact layer (impacted side). The damage area expanded away from impact centre as the impact energy increased in those zones. A sudden increase of absorbed energy between zones B and C (points 6-7) was observed indicating, what the authors called unstable damage, without being specific on the nature of the damage. In zone C, parallel to the equal energy line suggesting that the difference between the impact

![Figure 2.16 – Absorbed energy-impact energy response of woven fabric specimens [Atas and Sayman, 2008]](image-url)
energy and absorbed energy is almost constant in that zone, implying that the additional impact energy is absorbed by the specimen at that zone. At the end of zone C (point 13), increase of absorbed energy indicates major damage forming in the laminate which corresponds to the penetration threshold of the woven fabric laminates. Zone D represents the penetration of the specimen and zone E represents the post-penetration event caused by pure friction (see Figure 2.7(d) – specimen “17”). Figure 2.17 shows images of the damage for different specimens at the impact (back) and exit (front) layers.

![Images of the damage growth on different specimens at the impact and exit layers](image)

In section 2.3.1, the impact experiments on woven and cross-ply carbon/epoxy laminates examining by Kim and Sham (2000) were described. Kim and Sham (2000) also compared the damaged area of cross-ply laminates and woven fabric laminates with different numbers of layers with respect to C-scan images of the impact and exit layer. They also investigated the relationship between damage area and impact energy. Figure 2.18 shows C-scan images of impact (front) and exit (back) layer of woven and cross-ply laminates with similar thicknesses. The damage in the woven fabric laminate had the shape of a cross lying in the warp and weft directions. In the cross-ply laminate, damage showed as delaminations paraller to the fibres at the $0^\circ$ direction. The damaged area of the impact layer was larger in the woven laminate than
in the cross-ply fabric laminate. However, the much larger damage area of the cross-ply laminate in the exit layer makes the total damage area of the cross-ply laminates larger than the total damage area of the woven fabric laminates.

![Images of the c-scan of impact (front) and exit (back) layer of (a) woven and (b) cross-ply laminates](Kim and Sham, 2000).

Siow and Shim (1998) impacted woven fabric (0/90/-45/+45/0/90), carbon epoxy composite plates using drop weight impact tests with different tip shape (sharp and hemispherical) and different masses of impactor. Each impactor was dropped from two different heights and after the impact tests the specimens were inspected by C-scan. The results show that the delamination area increased linearly with impact energy for both impactors, but the increase for the sharp impactor was steeper than the hemispherical impactor. They also showed that the threshold energy (energy after which initiation of damage occurs) for a sharp impactor is lower than for a hemispherical impactor, indicating that it was easier for the sharp impactor to induce impact damage within the composite. By examining the specimens visually, it was noticed that for the same impact energy, the specimen impacted with a sharp impactor had more fibre damage and delaminations than a specimen impacted with a hemispherical impactor and that fibre fracture was a more common failure mode for the woven fabric rather than cross-ply laminates. This is believed to be due to the
interweaved tows, resulting in stress concentrations at the cross-over points, causing the fibres to fail more easily than in the cross-ply laminates.

### 2.3.3 Modelling of impact behaviour

Many studies have been made concerning the relationship of threshold damage load (load at which initiation of damage occurs) and the thickness of the specimens under impact tests [Abrate, 1991; Davies and Zhang, 1995; Belingardi and Vadori, 2002; Davies et al, 1996; Sutherland and Soares, 1999; Schoepner and Abrat, 2000; Caprino et al, 1999]. Zhou (1995) investigated the possibility to predict impact damage thresholds of glass fibre reinforced laminates by using the impact response from a drop weight impact tests. He tested E-glass and S-glass woven fabric laminates with polyester and phenolic resin systems respectively, with two different thicknesses. The laminates were cut to circular plates with two different testing areas with a diameter of 100mm and 500mm. Using the force-time and energy-time responses, the threshold damage load and threshold energy at which delaminations are initiated can be found, as was already discussed in the previous section, from the sudden drop of load. Then he plotted load against impact energy for all tested specimens to see if a similar trend exists. The impact force in the small plates shows the damage initiation clearly (sudden drop) which was similar to the damage initiation identified on the load-time responses of the individual tests. After that, the load increased linearly as impact energy increased, suggesting no change in the damage mode, and finally it became constant, indicating that the laminates cannot carry higher loads due to fibre fracture. Due to the fact that delaminations are driven by shear stress, the initiation of damage should be independent of plate diameter and therefore, the larger plates should have the same thresholds as the smaller plates. The larger plates though absorbed more energy at the same load and could carry higher loads and the reason for these was believed to be due to the higher in-plane stresses of small plates than of higher ones. This shows that the threshold values depend on the in-plane dimension of the laminate. One suggestion for the load to initiate and drive delaminations produced by Zhou (1995) can be drawn by considering that delamination is given as follows:

\[ P = \frac{4\pi}{3} \dot{tr} \]  

(2.1)
where $P$ is the impact force, $\tau$ is the shear stress, $t$ is laminate thickness and $r$ is the radial co-ordinate at which delamination is assumed to be initiated.

Davies and Zhang (1995) further investigated Equation 2.1 by assuming the plate used for impact test is perfectly isotropic and the delamination is perfectly circular, they suggested an alternative equation for the threshold damage load for delamination initiation, $P_c$:

$$P_c = \frac{2\sqrt{2\pi}}{3} \left( \frac{E G_{IIc}}{1-v^2} \right)^{1/2} t^{3/2}$$

(2.2)

where $E$ is the Young’s modulus, $v$ is the Poisson’s ration, $G_{IIc}$ is the mode II critical strain energy release rate and $t$ is the thickness of the plate. Davies and Zhang (1995) tested this formula for angle-ply carbon epoxy laminates with a range of thicknesses from 1mm to 4mm which showed a good agreement. They also developed a finite element model which was in agreement with Equation 2.2. Furthermore, Davies et al (1996) used Equation 2.2 on thicker specimens; woven glass/polyester laminates with a range of thickness of 10mm to 25mm, and found that the Equation 2.2 did not apply for laminates with thickness of 10mm to 25mm.

Schoeppner and Abrate (2000) used 500 low velocity impact load-time histories of graphite/epoxy, graphite/PEEK and graphite/BMI material systems of difference thickness to investigate the threshold loads for low velocity impact on composite laminates. The graphite/epoxy laminates were fabrigated using six different lots of prepreg tape, whereas the graphite/PEEK and graphite/BMI laminates were fabricated from a single prepreg lot. The laminates had different numbers of plies from 9-96. Each ply thickness was about 0.14mm and the thickness of the specimens varied from 1.3mm to 13.5mm. By plotting the threshold damage load against laminate thickness, they concluded the threshold damage load at which initiation of delaminations occurred varies with laminate thickness to the 3/2 power as predicted by Equation 2.2.

Another test of Equation 2.2 was carried out by Caprino and colleagues (1999) who performed low velocity impact tests on graphite/epoxy laminates with different thicknesses in the range of 0.5mm to 4mm using drop weight impact tests. They also
found that for these specimens Equation 2.2 is valid and that the threshold energy where the initiation of delamination occurs and penetration energy (energy needed to penetrate a specimen) also are proportional to thickness to the 3/2 power. Caprino et al (2003) propose a model to predict the elastic energy stored at the first failure resulting in matrix cracks and delaminations in circular composite plates loaded at the centre. By using a model of the load-displacement curve of simply supported circular plate loaded at the centre [Caprino et al, 2002; Timoshenko and Woinowsky, 1959], and Equation 2.2, they suggested that the threshold energy, $U$, can be calculated as follows:

$$U = \frac{2Ew_o^2t}{BD^2} \left( t^2 + A \frac{w_o^2}{2} \right) + \frac{2k_iw_i^{5/2}}{5}$$  \hspace{2cm} (2.3)$$

where $E$ is the Young’s modulus, $w_o$ is the deflection, $A$ and $B$ are two constants depending on the boundary conditions and material constants, $D$ is the plate diameter, $t$ is the thickness, $k_i$ is the rigidity of the plate and $w_i$ is the indentation (i.e the difference in displacement between the top and the back face of the plate at the point of load application. This model is based on the assumption that the first failure resulting in matrix cracks and delaminations is due to interlaminar shear stresses and also depends on the impactor diameter. The model was experimentally validated by Lopresto and Caprino (2004) and the results were in a good agreement with the model.

Furthermore, Caprino and Lopresto (2001) propose an empirical relationship between the penetration energy, $U_p$, laminate thickness in mm, $t$, laminate volume fraction, $V_f$, and impactor’s diameter in mm, $d$. The relationship is given by:

$$U_p = 0.49(tV_fd)^{1.4}$$  \hspace{2cm} (2.4)$$

This relationship was derived using data from impact tests of glass fibre and for carbon fibres laminates of different resin types and fibre architecture taken from the literature.
An alternative empirical approach to modelling the energies in an impact test has been investigated by Martello et al (2006). They suggested a method for representing the relationship between the absorbed and impact energies in drop weight tests on carbon woven fabric CFRP laminate having four different stacking sequences. They performed partial penetration and full penetration on the laminates, with different impact energy values and impact velocities. In this approach, the energy absorption of a composite panel during a particular test ($U_{abs}$), the impact energy for that test ($U_{imp}$), were normalised by the penetration energy of the specimen ($U_p$). Penetration energy was chosen to be the most suitable normalised parameter, because not only it represents the limiting impact condition, but it also represents the maximum energy absorption of a laminate. They named $\frac{U_{imp}}{U_p}$ as the “impact intensity coefficient” and $\frac{U_{abs}}{U_p}$ as the “absorption coefficient”. By plotting the impact intensity coefficient against the absorption coefficient for different laminates they were able to suggest that a remarkably simple empirical relationship connects these energies; i.e.

$$\frac{U_{abs}}{U_p} = \left(\frac{U_{imp}}{U_p}\right)^2$$  \hspace{1cm} (2.5)

Figure 2.19 shows the absorption coefficient-impact intensity coefficient response of the Martello et al (2006) results and of other results they found from the literature.

![Figure 2.19](image-url)
The results show a good agreement with Equation 2.5, which is represented by the solid line on the graph, although there is considerable scatter in the experimental results. It is not clear why a relationship of this form should be valid, nor whether it would be applicable for impactors of different shapes. After discussing damage and damage modelling, the next section deals with methods to reduce impact damage.

### 2.3.4 Methods to reduce impact damage

A number of authors have discussed methods to improve impact resistance (e.g. Cantwell and Morton, 1991; Hosseinzadeh et al, 2006; Wei and Sandstrom, 1998b), but Greenhalgh and Hiley (2003) have provided a useful review of the most important methods such as 2D and 3D woven materials, stitching, z-pinning and using hybrid laminates with tougher matrix systems. They divide impact tolerance into two parts: impact resistance, which is the ability to sustain a given impact threat with a minimum amount of damage; and impact damage tolerance, which is the ability to sustain a given level of damage with minimum effect on the performance. All the methods mentioned could improve the impact tolerance in structures, but all had particular disadvantages, such as reduced undamaged performance or weight increases. They suggested that the best material for impact resistance applications was planar woven laminates, since they are relatively cheap and easy to fabricate. For impact damage tolerance, z-pinning was found to be the best material. Consequently, they suggested that 3D and 2D woven laminates in combination with stitching or Z-pinning are good options for the future.

In addition to the methods outlined above, an additional possibility to improve the impact behaviour of composites is to include shape memory alloys (SMAs). SMAs have high strength and are able to absorb and dissipate impact energy due to a unique property, superelasticity [Wei et al, 1998b]. Figure 2.20 shows the stress-strain response of different engineering materials. SMAs can dissipate a large amount of energy when loaded to failure due to a plateau in the stress-strain curve. The next section provides a short introduction to shape memory alloys.
The use of shape-memory alloys (SMAs) in the past decades has increased rapidly due to their scientific and technological potential. SMAs have two unusual abilities that make them unique. These abilities are the shape memory effect and pseudoelasticity (or superelasticity), which will be discussed later in this section. SMAs also have large recoverable strains (up to 8%) and high damping capacity [Wei et al, 1998a].

Shape memory alloys (SMA) are characterized by unique properties which ordinary metals and alloys do not have. The shape memory effect is the ability of deformed SMAs to return to their original shape upon heating, whereas superelasticity is the ability of strained SMAs to return to their original shape when the stress is removed. These unique properties were first observed in gold-cadmium in 1932. In 1962, William J. Buehler and co-workers discovered that nickel-titanium (NiTi) also has these properties [Srinivasan and McFarland, 2001]. NiTi is the most common SMA since it has been used in this project, more emphasis will be given to this alloy here.
Chapter 2

The unique properties of SMAs occur due to the rearrangement of atoms within the crystal structure. The low temperature structure of SMAs is called martensite which has a highly twinned crystalline structure, whereas the high temperature structure is called austenite which has a body-centred cubic structure. There are four critical temperatures where the phase transformations take place. \( M_s \) and \( M_f \) represent the start and finish temperatures of the martensite phase and \( A_s \) and \( A_f \) represent the start and finish temperature of the austenite phase [Srinivasan and McFarland, 2001].

As mentioned above, the shape memory effect is the ability of deformed shape memory alloys to return to their original shape upon heating [Ogin, 2006]. Every SMA has a characteristic temperature \( M_s \) below which, if the alloy is deformed, it returns to its original shape by heating to above \( A_s \). The alloy can produce a high force during the phase transformation and therefore it can be used as an actuator in different applications. A typical transformation of an SMA involves cooling from the austenite phase to martensite, the transformation starting at \( M_s \) and finishing at \( M_f \) were the SMA is 100% martensite. The transformation is reversible and the alloy can return to the austenite phase starting at \( A_s \) and finishing at \( A_f \) at 100% austenite. These transformation temperatures depend on alloy type and load used. The loop related to these transformation temperatures, \( M_s, A_s, M_f \) and \( A_f \) is called the hysteresis of an SMA. Figure 2.21 shows a schematic temperature cycle where the y-axis of the graph is the fraction of martensite in the material, \( \xi \). At \( M_f \) and \( A_s \), where the material is 100% martensite, \( \xi = 1 \) and at \( M_s \) and \( A_f \), where the material is 100% austenite, \( \xi = 0 \).

![Figure 2.21 - Schematic temperature cycle of SMAs showing the shape memory effect](image)

[Srinivasan and McFarland 2001].
Superelastic behaviour is the other unique property of SMAs that occurs when the alloy is strained at a temperature just above its austenite finish temperature. This is shown schematically in Figure 2.22. The applied stress transforms the austenite to stress-induced martensite (SIM) which makes the alloy increase strain at a constant stress. When the load is removed from the alloy, the martensite transform back to austenite and returns to its original shape.

Both the shape-memory effect and superelasticity can occur in the same alloy since the shape memory effect occurs below $A_s$ where as superelasticity occurs above $A_f$. Hence, which property occurs depends on the temperature of use in relation to the transition temperatures [Otsuka and Wayman 1998]. NiTi alloys are the most commonly used SMAs because of their good mechanical properties, shape-memory performance and corrosion resistance. NiTi alloys can be easily fabricated to various sizes and forms [Wei et al, 1998a].

Figure 2.23 shows a typical tensile stress-strain response of a NiTi wire taken to failure. The wire, 0.8mm diameter, was tested at 303K at which temperature; it will show the superelastic effect. Two yielding points were noticed on the response when applying stress on the wire. The first yielding ($Y_R$) was due the start of deformations from the rearrangements of R-phase variants. The second yielding ($Y_M$) was due to the start of deformation from the stress-induced martensite. After the specimen was 100% martensite and the stress continue to increase, slip deformation began. Fracture of the specimen occurred at 15% strain [Otsuka and Wayman, 1998].
A number of authors have investigated different mechanical properties of SMA alloys which are not essential to this work, so will be mentioned only briefly. Miyazaki et al (1985) and Tsoi et al (2004a) experimented on the effect of different thermomechanical treatments on the stress-strain behaviour and Tobushi et al (1998), Chen et al (2001) and Nemat-Nasser and Choi (2005a and 2005b) investigated the stress-rate behaviour (both finding SMAs, to be very strain-rate sensitive). Pieczyska et al (2005) examined the stability of the hysteresis loops of superelastic SMA wire loaded into the plateau region, and then unloaded, and found a small reduction in the energy dissipated and the energy recovered in the first 20 cycles, but little change after that. In addition, Lau et al (2002) have investigated the effect of pre-strain on the bonding of a shape-memory NiTi wire to epoxy. A single NiTi wire with 0.5mm diameter and with different levels of pre-strain (4% to 10%) was embedded to an epoxy cylinder with 10mm diameter. Samples without pre-strain wire were heated at different temperatures to investigate their surface conditions. The 4% and 6% pre-strain SMA wires were well bonded with the epoxy matrix, whereas the 8% pre-strain SMA wire was debonded from the epoxy matrix and shear cracks were observed. Initiations of small cracks along the circumference of the wire were found on the 6% pre-strain SMA wire/epoxy sample. The next section reviews the work which has been carried out on composite materials with embedded SMA wires, focusing particularly on the impact behaviour.

Figure 2.23 – Stress-strain response of 50:50NiTi alloy wire [Otsuka and Wayman, 1998].

![Stress-strain response of 50:50NiTi alloy wire](image-url)
Chapter 2 Literature Review

2.5 Composite materials with SMA wires

Shape-memory alloy (SMA) wires have been embedded in composites to improve mechanical properties such as damage tolerance, vibration and damping properties. Paine and Rogers (1994) seem to have been the first to suggest the use of SMA wire as reinforcement in composite materials to improve the impact resistance. They tested cross-ply graphite/bismaleimide composites of configuration [02/902/021, with and without superelastic NiTi SMA wires. The SMA wires were placed at the lower 0/90 ply interface and had a volume fraction overall, of 2.8%. The drop weight impact test method was used with a spherical-nosed impactor of 16mm diameter. Different heights for the drop weight were used to achieve energies in the range 2.4J-23J. By comparing graphite specimens with and without wires it was found that for high-energy impacts, the SMA wires prevented perforation of the specimen. It was also noticed that the peak impact force of the specimens with wires was higher than for the specimens without wires, for the same impact energy. This means that the specimens with SMA wires had a better impact resistance than composites without SMA wires.

Schrooten et al (2002) also investigated hybrid composites reinforced with SMA wires. Their aim was to select the appropriate SMA wire to reinforce a Kevlar/epoxy composite and three NiTi were chosen to be investigated. The composites were reinforced with pre-strained SMA wires with different volume fractions, diameter and spacing. The composites were tested with DSC, thermomechanical analyzer, static tensile tests, impact tests and mechanical fatigue test. Using an in-house built impact apparatus, the impact performance of the composites was investigated for impact energy range of 6J-18J. Tests of the composite materials with SMA wires showed that the composites have excellent mechanical properties and functional integrity. Pull-out tests on wires embedded in epoxy resin showed satisfactory results on the bonding of the SMA wire to the epoxy resin. They also produce a model to predict the thermomechanical behaviour of SMA wires and, using a simple force balance, the resulting composite behaviour.

An extensive series of impact tests was carried out by Tsoi et al (2003) who used sixteen-layer glass fibres/epoxy pre-preg with NiTi or NiTiCu SMA wires and
stainless steel wires with a volume fraction between 0.45% to 1.8% in composites with up to 16 plies (labelled number 1 on the impact face and number 16 on the exit face). The impact results showed that there is less than 1% difference in the energy adsorbed, and peak load during impact, for wires positioned between the 4th and 5th, 8th and 9th, and 12th and 13th layer when compared to samples with no wires. The wires positioned in the last two layers (15th and 16th) showed an increase of 25% for energy absorption and 10.4% for peak load for a wire volume fraction of 0.9%. For a wire volume fraction of 1.8% this decreased to 19% and 5.8%, respectively. Figure 2.24, taken from the paper, is supposed to show energy absorption for different wire positions and wire volume fractions. They claimed that for better impact resistance, the density of the wires should be higher, but this cannot be seen in the figure below. Also, it is not clear how 30J-35J of energy can be absorbed if the impact energy was only 6J.

![Figure 2.24](image)

*Figure 2.24 – Energy absorbed of the wires at different position in the composite and different volume fractions [Tsoi et al, 2003].*

Lau et al (2004) also impact tested SMA-reinforced composites, using ten-layer woven E-glass fabric composites stitched with SMA wire. They compared the specimens with unstitched ten-layer woven E-glass fabric composites. The SMA wire used was NiTi wires with 0.22mm diameter. Two different wire spacing were used, 20mm and 12mm. The wires were trapped inside the tows. Drop weight impact test were used to test the samples. In addition to impact tests, tensile tests and vibration
property tests were performed on the composites. The results showed that samples with stitched SMA wires produced smaller delamination energy than the unstitched samples. The unstitched samples had more shear cracks than the stitched samples.

A number of authors have studied the effect of introducing SMA wires in the thermomechanical response of the composite materials. Tsoi et al (2004b) studied in detail the thermomechanical characteristics of SMA composites, having chosen NiTiCu wires in an earlier investigation [Tsoi et al, 2004a]. These wires showed larger recovery stresses, better cyclic stability and smaller hysteresis compared to other NiTi wires investigated.

Psarras et al (2001) and Parthenios et al (2001) investigated Kelvar 29/epoxy composites with and without NiTiCu wires with laser Raman microscopy. The SMA wires had a diameter of 0.15mm and 3% pre-strain. Three or nine wires were placed in the middle of two layer Kelvar 29/epoxy specimens. The composite without wires consisted of four layers of Kelvar plies. The residual thermal stresses generated in the composites, due to the high temperature curing process compared to the martensite finish temperature, were measured. They observed that increasing the volume fraction of the wires the stresses generated in the laminate were increased reaching high enough values to lead to plate instability even at low activation temperatures.

Zheng et al (2001) also investigated the thermal response of composites with different pre-strains of NiTiCu alloy wires. The recovery stress of NiTiCu wires was measured at different temperature for a range of pre-strain values (1%-6%). It was observed that the recovery stress rate decreased with increasing pre-strain, a phenomenon also observed by Sittner et al (2000).

It has also been suggested that incorporation of SMA wires can delay matrix cracking damage. Ogihara et al (2001) performed tensile tests on cross-ply glass fibre composites with and without SMA wires embedded between 90° and 90° plies and aligned in 0° direction. The wire used was NiTi with 0.05mm diameter. Some of the samples were embedded with heat treated and/or pre-strained (3.7%) SMA wires. The samples with heat treated and pre-strained SMA wires show the highest damage initiation stress. The authors considered that the shape-memory effect of the SMA
wires reduced the thermal residual stress in the 90° ply which, results in the enhancement of both the stress for damage initiation and the laminate strength.

Some researchers have also attempted to use finite-element modelling to model the impact behaviour of composite materials with embedded with SMAs. Birman et al (1996), Roh and Kim (2002, 2003) and Meo et al (2005) for example considered composite plates with embedded SMA fibres subjected to low-velocity impact. In general, the results suggest that the presence of SMA wires increases the impact resistance of the composites due to the ability of the SMA wires to absorb impact energy.

2.6 Summary

This chapter has briefly described the architecture of composite materials, before discussing impact damage and methods of improving resistance to impact damage including the use of SMA wires. An interesting suggestion has been made with regard to the relationship between impact energy, absorbed energy and penetration energy in impact tests. The work in this thesis will focus on the effect of SMA wires on damage development in composite materials and will also investigate whether the energies involved in impact tests can be related in a simple manner. The next chapter will present the methods used for the preparation of the specimens to be investigated and the procedures followed for the testing of these specimens.
Chapter 3

Experimental Methods

3.1 Introduction

In this chapter the methods used to prepare and carry out the experimental work are described. In the first part of the chapter, details are given about the materials used and manufacturing procedure of the laminates. In the second part, the methods used for carrying out and obtaining the data for the impact test and tensile test are explained together with the method for measuring the volume fractions of fibre and wire reinforcement in the laminate. The last part of the chapter outlines the macroscopic and microscopic analysis of the specimens.

3.2 Materials & Lamination

The specimens were made with a tri-component epoxy resin reinforced with E-glass fibres. Two different glass reinforcements and ten different kinds of laminate were manufactured during this study. The different kinds of laminate were eight-, four- and two-layer of woven fabric reinforced laminates with and without additional copper or superelastic SMA wire reinforcement. In addition, cross-ply laminates, [0/90]s, with nominal ply thickness of 0.25mm were also manufactured. In this section, the manufacture of the two glass reinforced systems is described.
The glass fabrics used were Fothergill Engineered Fabrics Ltd., YO94 E-glass plain weave fabric. This was a woven fabric made with similar number of warp and weft tows consisting of three finer bundles twisted together, with a tex value of 22. The weight of the cloth is 182gm² and the thickness is 0.15mm. It is marginally unbalanced with 142 and 126 ends and picks per 100mm, respectively. The warp and weft tow repeat with approximately 0.8mm average distance between the midpoints of warps tows and the weave is open in nature. The tow width and the gap between adjacent tows are approximately 0.6mm and 0.2mm respectively [Manger 1999]. The density of E-glass fibres is taken to be 2.56gcM⁻³ [Belmonte 2002]. Figure 3.1 shows a picture of a sample of the woven fabric used in this work. The cross-ply composite laminate manufactured was a simple [0/90], using 600TEX E-glass, and each ply was about 0.25mm thick.

![Figure 3.1 - Picture of a sample of woven fabric used in this project.](image)

The matrix used for both reinforcements was a Bisphenol-A 67 resin 300 (Shell Epikote 828), with nadic methyl anhydride (NMA) curing agent and Ancamine K61B catalyst, and the composition by weight of the resin was 100: 60: 4, respectively. This resin was chosen, because it has a refractive index similar to that of the E-glass fibres, readily wets the glass and it produces a translucent composite material, which is extremely important for the experiments of this study. The density of the epoxy resin matrix was taken to be 1.21gm⁻³ [Belmonte 2002]. The yield strength of the epoxy
measured in compression is 96MPa [Lee, 1992]. The steps to laminate the cross-ply laminate and the woven fabric composite, additionally reinforced with wires, were as follows.

The SMA wire used to reinforce some of the specimens was superelastic NiTi alloy S from Memory-Metalle GmbH. The wire was 0.152mm diameter, straight annealed with an \( A_f \) temperature of around 0°C. The measured compositional average is around 50.8% Ni [www.memory-metalle.com]. The copper wire used for this work was obtained from Comax engineered wires with the same diameter as the SMA wires (0.152mm). This was done so a direct comparison between the specimens with SMA wires and the ones with copper wires could be made.

The procedure for manufacturing the woven fabric reinforced laminates without wires was as follows. Layers of woven fabric of dimension 450mm \( \times \) 450mm were marked with a permanent marker pen along the crimps in each orthogonal direction. This produced four equal squares of dots, 150mm \( \times \) 150mm, as shown in Figure 3.2, which enabled any shear in the cloth to be identified and corrected during the lay-up and made sure that each orthogonal direction was align. Furthermore, the marked dots were very useful during the cutting of the specimens from the lamina after lamination.

![Figure 3.2 - Sketch of a layer of woven fabric marked before lay-up process.](image)
Next the resin matrix (about 1kg for eight-layer woven fabric composite and 370g for cross-ply laminate) was prepared by mixing the resin with the hardener and the catalyst, followed by a degas of the mixture at 50°C, to assist resin flow and to eliminate voids. Two separate waxed glass plates of dimension 380mm × 380mm were used in the lay-up of the woven fabric. They were cleaned by removing any prior wax by a razor blade and wiped by methanol. These plates were pre-heated in the oven at 50°C after applying a layer of wax on them, to help the flow of the resin.

A square piece of Melinex coated with silicone was placed on one of the glass plates and resin was poured on its middle. One layer of woven fabric cloth was placed slowly on top on the glass plate with the poured resin and a layer of Melinex without silicon coating was placed on top. The resin was then spread manually, using a straight edged tool, and then the cloth was aligned by placing the marked crimps on the same order as marked paper placed below the glass plate. After the alignment any remaining voids were removed manually.

This process was repeated on another layer of woven fabric cloth using the other glass plate, with the only difference that both pieces of Melinex were with no silicon coating. The two top Melinex layers were removed and the two cloths were placed on top of each other, aligned together and any remaining voids were removed. If required a further layer was prepared and placed on top of these two layers and aligned. This process was continued until the required number of woven fabric layers was reached. Then the top Melinex layer was replaced with a silicon coated Melinex layer, a final removal of voids was done and the second glass plate was placed on top of the laminate. The laminate was then placed in the oven and cast iron weights were applied to give a pressure of about 7kPa for eight-layers, 3.5kPa for four-layers and 1.8kPa for two-layer composites. All the laminates were cured at 100°C for 3 hours [Belmonte 2000]. Four circular specimens were cut from each laminate with a water-cooler diamond saw. The diameter of these specimens was 140mm as was suggested by the CRAG manual [CRAG test 403]. These specimens were tested in the specially design impact rig which is described in section 3.3 below.
For laminates additionally reinforced with wires, the procedure was modified to include a layer of wires as follows. For the specimens with additional wire reinforcement, the first step was to wind the wires onto a frame with dimensions 420mm × 420mm. The frame had eight combs to support the wires with dimensions 150mm × 5mm, two on each side (side by side). The combs were attached on the edge of the frame at three points with screws. Each comb had 100 teeth which produced a minimum wire spacing of 1.5mm. Figure 3.3 shows a sketch of the comb.

![Sketch of a comb.](image)

The wire was tied with a knot at the beginning of one of the combs and passed manually through the first gap of the comb and through the corresponding gap of the comb on the opposite edge of the frame, and then passed through the next gap etc, as indicated by the arrows in Figure 3.4. This process was continued until the required amount of wire in one direction was wound. Then the wire was tied as a knot on the end comb. Sticky tape was used to cover the wire on top of the frame to make sure that it did not get loose. Having wound the wire in that direction, the same was then carried out for the transverse direction.

The frame with the wires was placed between the last two layers of woven fabric cloths. Then the procedure for producing the woven fabric laminate was continued as described above for specimens without wires. The volume fraction of SMA wires in the specimens was estimated to be 0.8%, 1.5% and 2.4% for eight-layers, four-layers and two-layers of woven fabric respectively by a simple calculation of finding the volume of the wire that would be in a square specimen of dimension 100mm × 100mm and then dividing by the volume of the specimen itself. This will be analysed more fully in Chapter 4.
With regard to the manufacture of the cross-ply laminates, the first step for the lamination of the cross-ply laminates was the winding of the glass fibres tows onto a steel frame of 420mm × 420mm. The steel frame was placed on a revolving motor so that the frame rotated about its axis pulling the fibres from a guide screw moving from left to right, and vice-versa, at constant speed to wind the tows onto the frame. The speed of the machine controls the resultant thickness of the plies. The rotating motor was set at 120rpm and the guide screw at 434rpm giving plies of 0.25mm thickness. After the inner 90° plies were wound, the frame was rotated 90° degrees so that the outer 0° plies were wound. Figure 3.5 shows a sketch to represent the winding of the fibres.

Figure 3.5 – Sketch of winding glass fibres in a frame.
The frame with fibres was then placed in a large container connected to a vacuum pump on top of a layer of silicon coated Melinex and a hot plate (~140°C). The resin was prepared the same way as for the woven fabric lamination and was spread on top of a layer of silicon-free Melinex and a cold plate (left in the freezer overnight) and then left for a few seconds to cool down. Then the resin was placed on top of the frame in the vacuum container by carrying the Melinex and reversing it on top of the frame. A waxed glass plate was placed on top of the frame with 5kg cast-iron weights on it. The vacuum basin was then sealed and left for 20 minutes for the laminate to degas. Then the frame was taken out of the vacuum basin and the silicon-free Melinex was replaced with a silicon coated one. Any voids left were removed manually using a straight edged tool. The lamina was then placed in an oven between two jig plates with 45kg of weight on top and left to cure for 3 hours at 100°C [Barton et al, 2001].

For the impact specimens, four circular specimens were cut from each laminate using a water-cooler diamond saw. The diameter of these specimens was 140mm. The specimens were post-cured at 150°C over a period of 2 hours, left at that constant temperature for another 3 hours, and then allowed to cool down in the oven to room temperature overnight. Figure 3.6 shows a schematic of the cross-ply laminates that were manufactured.

Figure 3.6 – Schematic of a cross-ply laminate.
3.3 Impact tests

A servo-hydraulic machine was used for the impact testing. Figure 3.7(a) shows a sketch of the impact rig and Figures 3.7(b) and 3.7(c) show pictures of the actual rig and the impactor, respectively. The rig was designed to be placed at the top of the machine, located below the load cell. The circular specimens of 140mm diameter were clamped so that the area exposed for impact was of diameter 100mm. The rig consisted of a cage and the circular composite specimen was located at the base of the cage. A video camera was fixed within the cage so that it could view the exit surface of the impacted specimen. A glass impactor in a shape of a sphere of diameter 16mm was mounted on a spigot clamped within the actuator; glass has been used in order to minimise the shadow of the impactor in the video recording. The impactor was driven by the lower grip upwards producing an impact at the centre of the panel.

Three types of impact test were used. The first type is where the impactor is driven at constant velocity completely through the specimen ("single impact test"). Generally, this required an impactor displacement of about 18mm. The second type of test was a "multiple impact test". During a multiple impact test the impactor was driven at constant velocity into the specimen to a certain displacement e.g. 2mm from a datum where the impactor just contacted the specimen surface. Then, the impactor was withdrawn back to its initial position at the same velocity. The impactor was then driven to a higher displacement during the next impact i.e. 5mm and again returned to its initial position. This process was repeated with increasing impactor displacements of 2mm, 5mm, 8mm, 10mm, 12mm, 15mm and 18mm. The third type of impact test is called a "partial penetration impact test". This test is similar to the multiple impact test but instead of one specimen impacted at seven different displacements a new specimen was used for each displacement. Using this type of test, it was possible to remove each specimen from the rig and examine the specimens by microscopic analysis to investigate damage development for different impact displacements.
For each type of impact test, load-displacement graphs were recorded showing the variation of load with impactor displacement during the experiments. From these graphs, the time that different types of damage occurred to the specimen can be estimated (since the impactor velocity is known) and these graphs can be linked with the video camera images of damage. For the multiple impact tests and the partial penetration impact tests, the maximum displacement of the impact was easy to match.
up with the video images, and therefore appropriate images were easily extracted. For a single impact test (full penetration) the process was more complicated. The video image taken at maximum displacement (18mm) was found and the time that displacement was noted. Knowing the speed of the impactor (4mmsec\(^{-1}\)) the time at particular displacement was estimated and the respectively images could then be extracted from the video.

For all the impact tests, the energy absorbed was found by calculating the area under the load-displacement curve, using a Riemann integral [Shilov and Gurevich, 1978]. A schematic of a single impact test is shown in Figure 3.8. Points A, B and C are three points on the load-displacement curve. A rectangle is created from points A and B, using as the rectangle width the difference between the displacements of the two points and the heights the load at point A plus half the difference between the loads at points A and B. The sum of all the rectangles is equal to the area under the load-displacement response and therefore the energy absorbed during and impact test (the extra triangles formed from the rectangles above the line of the graph are cancelled out by the identical triangles that are formed below the line of the graph). In the case of the multiple impact tests, overlapping areas need to be taken into account so that the energies are not “double counted”.

![Schematic graph of a single impact test](image)

*Figure 3.8 – Schematic graph of a single impact test used to illustrate the calculation of absorbed energy during an impact test.*
Chapter 3  

**Experimental methods**

### 3.4 Nomenclature of the impact tested specimens

The woven fabric reinforced impact test specimens, impacted with single or multiple impact tests, were named in a specific way and an example is shown in Figure 3.9. The name reveals that the specimen is an eight-layer woven fabric specimen without wires impacted with multiple impact test at 4mmsec⁻¹.

![W 8 N 04 M - 01](image)

*Figure 3.9 – Example of a name of an impacted woven fabric specimen.*

The first letter (i.e. W) implies the type of glass reinforcement of the specimens, which in this case is woven. The following digit (i.e. 8) reveals the number of woven layers in the specimen (e.g. 8=eight-layers, 4=four-layers and 2=two-layers). The second letter of the name (i.e. N) implies if the specimen is reinforced with copper, SMA or no wires (e.g. N=none, C=copper and S=SMA). The two following numbers (or three in some cases) show the speed of the impactor during the impact test (e.g. .08 for 0.08mmsec⁻¹, 04 for 4mmsec⁻¹ or 200 for 200 mmsec⁻¹). The last letter (i.e. M) implies the type of impact experiment that the specimen was tested (e.g. M=multiple and S=single). Lastly the number at the end (i.e. 01) identifies the specimen within this category.

For partial penetration impact tests, the nomenclature of the specimens was a bit different. For woven fabric specimens impacted with partial penetration impact tests, the presents (or absent) of wires is indicated in the name, same way as above (e.g. N=none, C=copper and S=SMA), so as the impact displacement in the specific impact. For example, woven fabric specimens with and without copper or SMA wires impacted to 2mm in impact displacement are named as N-02, C-02 and S-02, respectively. For cross-ply glass fibre specimens impacted with partial penetration impact tests the type of glass reinforcement (e.g. CPF) and the impact displacement is indicated in the name. Therefore, as an example, a cross-ply glass fabric specimen impacted to 2mm in impact displacement was named CPF-02. Table 3.1 shows all the specimens tested with the type of impact test, impactor’s velocity and specimen thickness.

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<th>Type of impact test</th>
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<tr>
<td>W2C04M-05</td>
<td>Multiple</td>
<td>4</td>
<td>1.03</td>
</tr>
<tr>
<td>W2S04M-01</td>
<td>Multiple</td>
<td>4</td>
<td>0.99</td>
</tr>
<tr>
<td>W2S04S-02</td>
<td>Single</td>
<td>4</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Table 3.1 – Details of specimens tested using multiple and single impact tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type</th>
<th>Number</th>
<th>Impact Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2S04S-03</td>
<td>Single</td>
<td>4</td>
<td>1.02</td>
</tr>
<tr>
<td>W2S04M-04</td>
<td>Multiple</td>
<td>4</td>
<td>0.99</td>
</tr>
<tr>
<td>W2S04S-05</td>
<td>Single</td>
<td>4</td>
<td>1.02</td>
</tr>
<tr>
<td>W2S04S-06</td>
<td>Single</td>
<td>4</td>
<td>1.06</td>
</tr>
<tr>
<td>W2S04M-07</td>
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<td>4</td>
<td>1.02</td>
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<tr>
<td>W2S04M-08</td>
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<td>0.97</td>
</tr>
<tr>
<td>W2S04M-09</td>
<td>Multiple</td>
<td>4</td>
<td>1.04</td>
</tr>
</tbody>
</table>

3.5 Tensile tests

A quasi-static tensile testing machine was used to perform tensile tests on the SMA and copper wires, and on the different types of specimens.

3.5.1 Tensile test of wires

Gripping of the wires to perform the tensile tests proved to be very difficult and several methods were attempted. The most successful method was to use two aluminium tabs of dimension 20mm × 20mm to grip each end of the wire. The wire was passed through slots made in the tabs and tied with a knot. Then the wire was passed between the tabs which were glued around the wires and left to cure overnight. The gauge length of the wire specimen was taken to be the length of the wire between the surfaces of the tabs and was set to be 100mm. A 100N load cell and a displacement rate of 5mm min⁻¹ were used in the Instron quasi-static testing machine to carry out these experiments. Two types of tensile tests experiments were carried out on the SMA and copper wires. The first experiment was loading the wires until failure and the second experiment was to load and unload the wire to different extensions. Although the method of gripping worked well with the copper wires, in the case of the SMA wires some slipping of the wires occurred occasionally.

Stress-strain graphs were plotted showing the load-displacement response of the SMA wires and the copper wires. From the slope of the elastic region of these graphs the Young’s modulus of the SMA wires was estimated and the energy absorbed to different strains was calculated from the area under the graph.
Chapter 3 Experimental methods

3.5.2 Tensile test of composite specimens

Rectangular coupons of 100mm x 20mm of each kind of laminate were cut to be investigated in tensile tests to determine the Young’s modulus. Each specimen was cycled three times at a speed of 0.5mm/min between strains of 0.02% to 0.2%, which was below the strain for damage onset in the specimens. An extensometer (Instron 2.5 Dynamic 2620-602) was used to measure the strain of the specimens and the Young’s moduli of the specimens were determined from the stress-strain data.

3.6 Volume fraction determination

The volume fraction of the reinforcing glass fibres and the wires (copper and SMA) in the composites was found by performing burn-off test on small samples of each type of specimen. A 15mm x 15mm sample of a specimen was placed in a pre-weighed porcelain crucible, and weighed. Then the specimen was heated to 600°C for 3 hours so that the entire matrix was burnt-off. The crucibles with the fibres – and wires for some specimens – were weighed again. In the case of specimens with wires, both fibres and wires were weighed and then the wires were separated from the fibres and weighed again alone. The volume fractions were then calculated by using the formula for the relation between the volume fractions, the masses and densities, of the fibres, matrix and wires:

- For specimens without wires:

  \[
  V_{f\text{(fibre)}} = \frac{(m_f \rho_f)}{(m_f \rho_m) + (m_m \rho_f)} 
  \]  

  (3.1)

- For specimens with wires:

  \[
  V_{f\text{(fibre)}} = \frac{(m_f \rho_w \rho_f)}{(m_f \rho_w \rho_m) + (m_w \rho_f \rho_m) + (m_m \rho_w \rho_f)} 
  \]  

  (3.2)

Here \(V_{f\text{(fibre)}}\) is the fibre volume fraction, \(m_f\), \(m_w\) and \(m_m\), \(\rho_f\), \(\rho_w\) and \(\rho_m\) are the masses and the densities of the fibres, wire and matrix respectively.
Modifying the above formulae appropriately enables the volume fractions of the wires and of the matrix to be calculated in addition.

### 3.7 Macroscopic & microscopic analysis of impacted specimens

To identify the damage that occurred during the impact tests both macroscopic and microscopic studies were undertaken on impacted specimens. Impacted specimens of two-layer woven fabric reinforced composites, with and without copper or SMA wires, were subjected to the partial penetration impact experiments which generated different degree of damage depending on the maximum depth of the impactor. Pictures of the damaged specimens at different magnifications were taken using a microscope with an Axiocam camera installed. The purpose of this analysis is to identify the damage within the different types of specimens for different impact displacements and to try to determine the development of the damage as the impactor moved further inside the specimen. Additionally, it was important to compare the response of specimens with and without copper or SMA wires.

In addition to these macroscopic observations, an Axiophot Zeiss microscope with transmitting light and differential interference contrast (DIC) of standard magnification was used for microscopic observations and microscopic analysis were performed on two-layer woven fabric reinforced composites. Four different partial penetration displacements were chosen to be investigated microscopically: 2mm, 5mm, 8mm and 10mm. Specimen types investigated at these displacements were two-layer woven fabric reinforced composites with SMA wires, copper wires and without wires. Figures 3.10(a) to 3.10(d) shows where the specimens were cut after impact and the arrows show the cross-sections that were polished. Figure 3.10(a) shows the position of the cross-section investigated for the specimen impacted to 2mm, Figure 3.10(b) represents 5mm, Figure 3.10(c) is for 8mm displacement where two cross-sections were investigated, one through the middle of the specimen and the second within the stress-whitened zone, same for Figure 3.10(d), which represents 10mm displacement. The pieces were embedded in a mixture of epoxy resin and left to cure
overnight and the specimens were ground and polished to produce samples for observation in the microscope, the polishing details are shown in Tables 3.2 and 3.3.

![Figure 3.10](image)

**Figure 3.10 – Sketch of the areas cut out from the specimens of impact test for microscopic analysis. The displacements that were investigated are (a) 2mm, (b) 5mm, (c) 8mm, and (d) 10mm.**

<table>
<thead>
<tr>
<th>Grindng</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Pedemax / Planofel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen holder</td>
<td>6 Specimens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grinding media</td>
<td>SOC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grit/Grain size</td>
<td>500</td>
<td>1200</td>
<td>2400</td>
<td>4000</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed rpm</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure N</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time /min</td>
<td>Till plane</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 3.2 – Details of the grinding process.**

<table>
<thead>
<tr>
<th>Polishing</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Pedemax / Planofel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen holder</td>
<td>6 Specimens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polishing cloth</td>
<td>DP-plan</td>
<td>DP-dur</td>
<td>DP-dor</td>
<td>DP-chem.</td>
</tr>
<tr>
<td>Polishing media</td>
<td>Diamond spray</td>
<td></td>
<td></td>
<td>OP-S</td>
</tr>
<tr>
<td>Grain</td>
<td>6μ</td>
<td>3μ</td>
<td>1μ</td>
<td>0.25μ</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Blue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure N</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed rpm</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time /min</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10sec water</td>
</tr>
</tbody>
</table>

**Table 3.3 – Details of the polishing process.**
3.8 Summary

In this chapter, details were given for the in-house manufacture of the different glass reinforced laminates used in this project. The different laminates were eight-, four- and two-layers woven fabric specimens, with and without copper or SMA wires, and cross-ply laminates, [0/90]_s, with 0.25mm nominal ply thickness. Both types of woven and unidirectional glass-reinforced laminates were made using a tri-component epoxy resin. Burn off tests on samples of the different types of specimens were used to find the volume fraction of the different components of the specimens. Some laminates were cut to circular specimens of 140mm diameter and were used for impact testing.

A servo-hydraulic testing machine was used to perform the impact tests. A specially designed rig was placed on top of the machine and the specimens were clamped at the base of the rig in such a way so that the expose area for impact was of 100mm. A video camera was used to record the exit site of the specimen during impact and monitor the damage formed. A spherical glass impactor with 16mm diameter was driven into the specimen at a constant speed. Three different types of impact tests were performed; single impact tests, where the impactor is driven completely through the specimen; multiple impact tests, where the impactor is driven in and out of a single specimen at different displacements; and partial penetration impact tests, which are the same as the impact tests except that instead of using one specimen for all displacements, different specimens were used for each displacement.

Tensile tests were also performed on samples of copper and SMA wires and also on the different types of specimens. Two types of tests were performed on the copper and SMA wires. The first experiment involved loading the wire to failure and the second was to load and unload the wire to different extensions.

The final part of this chapter describes the preparation of specimens that were used in the macroscopic and microscopic analysis of two-layer woven fabric specimens, with and without copper or SMA wires, impacted with partial penetration impact tests. The next chapter presents the material properties of the woven fabric composites and wire (copper and SMA) properties.
Chapter 4

Material properties: Wire properties, reinforcement volume fractions and Young's modulus of the woven fabric composites

4.1 Introduction

In this chapter the superelasticity of the SMA wires is investigated and the energy required to break the SMA wires is compared with the energy required to break the copper wires which were embedded in the composites. The volume fractions of the constituents of the various types of composites are derived, and the results are used to predict the Young’s modulus of the various composite materials for comparison with the results of tensile test to determine the Young’s modulus of the composites experimentally.

4.2 Tensile test of the SMA and copper wires

The two kinds of wires used in this work were tested to investigate their stress-strain behaviour. From the tensile tests, the load and the extension of the wire were found. The sample of wire was end-tagged, as described in Chapter 3, and placed in a quasi-static machine to be tested. The gauge length of the wire was 100mm. The wire was extended by up to 7.6mm and then returned to its original length. Figure 4.1 shows the stress-strain plot for the wire. The plot is very similar with the schematic stress-strain plot shown in the literature (Chapter 2 – Figure 2.22).
The wire behaviour was typical of a superelastic wire. The stress increased linearly as the strain was increasing up to about 1.6% where the onset of stress-induced martensite began. The load stayed constant as the strain increased for about another 5%. After a strain of 7.6% the loading was interrupted in the test and unloading of the wire began. The unloading wire was again typical of superelastic SMA wire as the martensite transformed back to austenite. For this extension, no plastic deformation of the martensite occurred so there was no permanent strain. The hysteresis loop formed during the loading/unloading cycle is a measure of the energy dissipated and this was investigated further in subsequent tests.

![Stress-strain graph](image)

*Figure 4.1 – Stress-strain graph of specimen SLU1, a sample of SMA wire, tensile tested to a strain of 7.6%.*

Samples of specimen were loaded-unloaded to different extensions and the energy absorbed was calculated for each loading-unloading cycle. Figure 4.2 shows the load-extension graph of one of the specimens. For extensions of 1.7mm to 7.6mm, the unloading curves return the specimen to its original length. However, when the load takes the extension beyond the plateau (after 9mm extension) a permanent set occurs which increases with increasing applied extensions. It should be noted that the irregularities in the load-extension and stress-strain curves for the high extensions are due to slipping of the specimen in the grips.
Chapter 4

Material properties: Wire properties, reinforcement volume fractions and Young's modulus of the woven fabric composites

The area of the hysteresis loops, from load-extension plots, formed on each loading-unloading cycle was the energy dissipated by the specimen during the cycle. Table 4.1 shows the average values of the energy dissipated for each cycle, up to the highest strains tested taken from testing two samples of SMA wire.

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>0.002</td>
</tr>
<tr>
<td>4.7</td>
<td>0.021</td>
</tr>
<tr>
<td>6.6</td>
<td>0.033</td>
</tr>
<tr>
<td>7.6</td>
<td>0.038</td>
</tr>
<tr>
<td>9.7</td>
<td>0.048</td>
</tr>
<tr>
<td>11.4</td>
<td>0.061</td>
</tr>
<tr>
<td>17.2</td>
<td>0.154</td>
</tr>
</tbody>
</table>

Table 4.1 - Average energy absorbed by the SMA wires during the loading-unloading cycles.

Figure 4.3 shows the energy absorbed of each cycle plotted against the strain of the wire. The energy absorbed increased linearly with increasing strain within the plateau region (up to about a strain of 10%). Beyond the plateau the energy absorbed increased more rapidly.
Some specimens were taken to failure without cycling and the energy dissipated to failure was calculated. Figure 4.4 shows the stress-strain response of four samples of SMA wires taken to failure. The plots were altered so that the irregularities on the curves due to slippage of the SMA wires within the grips at high strain were removed. On average the SMA wires dissipated 0.165J/mm$^3$ to failure, and extended up to average 16% strain before failure. These tests also enabled the Young’s modulus of the wire to be calculated from the initial elastic region of the stress-strain curve and an average value of 38±3.4GPa was found which agrees with the values found in the literature (www.memory-metallic.com).
For the copper wires, Figure 4.5 shows a typical load-extension and stress-strain plot, with the wire loaded and unloaded to different extensions. For the first cycle, involving a displacement 1% strain, the sample showed plastic deformation, as expected. The samples failed after about 18% strain.

![Figure 4.5 - (a) Load-extension plot and (b) stress-strain plot of specimen CLUI, a sample of copper wire, loaded-unloaded to different extensions.](image)

Table 4.2 shows the average energy absorbed by the copper wire in each loading-unloading cycle for different strains, taken by testing two samples of copper wires. Figure 4.6 shows the energy absorbed-strain response of the copper wires. Each energy value is the sum of the total energies from zero extension up to the wanted extension. The relationship between the energy absorbed and extension is linear. It was noticed that for a given maximum strain, the superelastic SMA wire dissipates more energy than the copper wire.

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>0.003</td>
</tr>
<tr>
<td>5</td>
<td>0.011</td>
</tr>
<tr>
<td>7</td>
<td>0.008</td>
</tr>
<tr>
<td>8</td>
<td>0.004</td>
</tr>
<tr>
<td>10</td>
<td>0.008</td>
</tr>
<tr>
<td>12</td>
<td>0.008</td>
</tr>
<tr>
<td>18</td>
<td>0.025</td>
</tr>
</tbody>
</table>

*Table 4.2 - Average energy absorbed by the copper wires during the loading-unloading cycles.*
Figure 4.6 – Relationship between energy absorbed with respect to strain for copper wires.

Some samples of copper wire were taken to failure. On average, the copper wires dissipated 0.04J/mm³ which is about ¼ of the energy dissipated by the SMA wire. Figure 4.7 shows a comparison of a typical copper wire and SMA wire stress-strain curve. It is immediately clear that the SMA wire dissipates substantially more energy to failure due to the higher stress for the same strain.

Figure 4.7 – Stress-strain response of copper wire (specimen CB1) and SMA wire (specimen SB4) loaded until failure.
Chapter 4  
**Material properties: Wire properties, reinforcement volume fractions and Young's modulus of the woven fabric composites**

### 4.3 Volume fraction of the woven fabric specimens with and without copper and SMA wires

The volume fraction of the components of the different kinds of composites was found experimentally by performing burn-off test on four samples for each kind of woven fabric composites as described in Chapter 3. To find the volume fractions the average masses of the fibres and wires (if applicable) that were measured from the burn-off test were used. The mass of the matrix was taken to be the difference of the sample before burn-off and the masses of the fibres and the wires after testing. Equations 3.1 and 3.2 were used to calculate the volume fraction of the different components for each types of woven fabric composite.

- For specimens without wires:

  \[
  V_{f(\text{fibre})} = \frac{(m_f \rho_f)}{(m_f \rho_m) + (m_m \rho_f)} 
  \]

  (3.1)

- For specimens with wires:

  \[
  V_{f(\text{fibre})} = \frac{(m_f \rho_w \rho_f)}{(m_f \rho_w \rho_m) + (m_w \rho_f \rho_m) + (m_m \rho_w \rho_f)}
  \]

  (3.2)

where \( V_{f(\text{fibre})} \) is the fibre volume fraction, \( m_f, m_w \) and \( m_m, \rho_f, \rho_w \) and \( \rho_m \) are the masses and the densities of the fibres, wire and matrix respectively. Similar formulae enable the volume fractions of the wires and the matrix to be calculated in addition.

Table 4.3 shows the values of the measured volume fraction for fibres, wires and matrix for each type of woven fabric composite, with the standard error for each measurement (four specimens were used each time). The densities of the fibre, matrix and SMA wire were 2560 kgm\(^{-3}\) [Fothergill Engineered Fabrics Ltd], 1210 kgm\(^{-3}\) [Manger 1999] and 6450 kgm\(^{-3}\) [memory-metallic.com], respectively.
### Table 4.3 – Measurements of the volume fraction of the fibres, wires and matrix in the different types of woven fabric composites.

<table>
<thead>
<tr>
<th>Type of Composite</th>
<th>Fibre volume fraction</th>
<th>Wire volume fraction</th>
<th>Matrix volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight-layer woven fabric without wires</td>
<td>0.472 ± 0.003</td>
<td>-</td>
<td>0.528 ± 0.003</td>
</tr>
<tr>
<td>Eight-layer woven fabric with SMA wires</td>
<td>0.423 ± 0.002</td>
<td>0.0084 ± 0.0001</td>
<td>0.569 ± 0.002</td>
</tr>
<tr>
<td>Eight-layer woven fabric with copper wires</td>
<td>0.401 ± 0.002</td>
<td>0.0103 ± 0.0004</td>
<td>0.589 ± 0.002</td>
</tr>
<tr>
<td>Four-layer woven fabric without wires</td>
<td>0.427 ± 0.004</td>
<td>-</td>
<td>0.573 ± 0.004</td>
</tr>
<tr>
<td>Four-layer woven fabric with SMA wires</td>
<td>0.390 ± 0.005</td>
<td>0.0156 ± 0.0002</td>
<td>0.595 ± 0.005</td>
</tr>
<tr>
<td>Four-layer woven fabric with copper wires</td>
<td>0.367 ± 0.002</td>
<td>0.0196 ± 0.0004</td>
<td>0.613 ± 0.002</td>
</tr>
<tr>
<td>Two-layer woven fabric without wires</td>
<td>0.383 ± 0.004</td>
<td>-</td>
<td>0.617 ± 0.004</td>
</tr>
<tr>
<td>Two-layer woven fabric with SMA wires</td>
<td>0.302 ± 0.005</td>
<td>0.0238 ± 0.0006</td>
<td>0.674 ± 0.005</td>
</tr>
<tr>
<td>Two-layer woven fabric with copper wires</td>
<td>0.309 ± 0.004</td>
<td>0.031 ± 0.001</td>
<td>0.659 ± 0.005</td>
</tr>
</tbody>
</table>

4.4 **Young's modulus of woven fabric composites with and without additional copper or SMA wires**

Measurements of the Young’s modulus of the woven fabric specimens with and without reinforcing copper or SMA wires are presented in this section together with predictions of their moduli. The theoretical values were predicted from a series of simple assumptions using the rule of mixtures and compared to the actual values by tensile testing of coupons.

4.4.1 **Measurement of the Young’s modulus of woven fabric specimens with and without reinforcing copper and SMA wires**

As was described in Chapter 3, two samples from each type of woven fabric specimen were tested on a quasi-static testing machine by loading/unloading the specimens at a speed of 0.5mm/min in their elastic region between strains 0.02% and 0.2%. From the data of these tensile tests, the Young’s moduli of the specimens were found from the slope of the stress-strain curves (examples are shown in Figure 4.8). Table 4.4 shows
the measured values of the Young’s modulus of the different types of composites. For each type of composite, two specimens were tested and the results of both tests are shown in the table.

![Stress-strain curves](image)

**Figure 4.8** – Stress-strain curves used to calculate the Young’s moduli of two-layer woven fabric specimens (a) without wires and (b) with SMA wires.

<table>
<thead>
<tr>
<th>Number of fabric Layers</th>
<th>Type of composite without wires</th>
<th>Measured Values</th>
<th>Type of composite with copper wires</th>
<th>Measured Values</th>
<th>Type of composite with SMA wires</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Measured Values</td>
<td>Average</td>
<td>Measured Values</td>
<td>Average</td>
<td>Measured Values</td>
</tr>
<tr>
<td>2</td>
<td>15.9GPa</td>
<td>16.7GPa</td>
<td>15.95GPa</td>
<td>16.3GPa</td>
<td>16.55GPa</td>
<td>15.3GPa</td>
</tr>
<tr>
<td>4</td>
<td>19.7GPa</td>
<td>21.2GPa</td>
<td>16.7GPa</td>
<td>17.0GPa</td>
<td>15.55GPa</td>
<td>13.9GPa</td>
</tr>
<tr>
<td>8</td>
<td>21.1GPa</td>
<td>22.6GPa</td>
<td>20.55GPa</td>
<td>21.0GPa</td>
<td>19.3GPa</td>
<td>19.3GPa</td>
</tr>
</tbody>
</table>

**Table 4.4** – Measured values of Young’s moduli of different types of woven fabric composites.

### 4.4.2 Predictions of the Young’s modulus of woven fabric specimens with and without additional copper and SMA wires

To predict the value of the Young’s modulus of the composites, the woven fabric was simplified and treated as 0° plies and 90° plies of a cross-ply composite. Figure 4.9
shows a sketch of the woven fabric composite treated as a cross ply composite, with equal numbers of $0^\circ$ plies and $90^\circ$ plies, i.e. $(0/90)_s$.

To find the Young's modulus of the composite, first the Young's modulus for the $0^\circ$ and $90^\circ$ plies must be found and then combined together. Equation 4.1 was used to find the Young's modulus of the $0^\circ$ direction and Equation 4.2 was used to find Young's modulus in the $90^\circ$ direction.

\begin{equation}
E_{0^\circ} = V_f E_f + V_m E_m
\end{equation}

\begin{equation}
\frac{1}{E_{90^\circ}} = \frac{V_f}{E_f} + \frac{V_m}{E_m}
\end{equation}

where $E_{0^\circ}$ and $E_{90^\circ}$ is the Young's modulus of the $0^\circ$ and $90^\circ$ direction respectively, $V_f$ is the volume fraction of the fibres, $E_f$ is the Young's modulus of the fibres and $V_m$ and $E_m$ is the volume fraction and the Young's modulus of the matrix, respectively.

For a $(0/90)_s$ laminate, the rule-of-mixture modulus is given by to a good approximation by:

\begin{equation}
E_c = 0.5E_{0^\circ} + 0.5E_{90^\circ}
\end{equation}

The procedure to find the volume fraction of the fibres and the matrix in the composites without wires was described in section 4.3 above. Using Young's moduli values for the glass fibres and matrix of 70GPa and 4GPa [Fothergill Engineered Fabrics Ltd], respectively, Equation 4.3 was used to predict the modulus of the composites without wires.
For the composites with reinforcing copper or SMA wires, a similar approach was used. The woven fabric specimens were treated as two plies of 0° and two plies of 90°. However, the wire reinforcement was included as two additional wire/matrix layers, one with wires in the 0° direction and the other with wires in the 90° direction. The overall composite then consists of the 0/90 glass/epoxy plies and wire/epoxy layers. Figure 4.10 shows a sketch of this approach.

Figure 4.10 – Sketch of a woven fabric composite with reinforcing copper or SMA wires treated as additional wire/epoxy layers.

For the calculations, a nominal specimen with overall dimensions of 15mm × 15mm × 1 was considered to calculate the Young’s modulus. To find the contribution of each ply to the value of Young’s modulus, the thickness of each layer was taken into consideration. Figure 4.11 shows a cross section of the sketch of Figure 4.10 defining the thickness of the layers. From the sketch, t₁ is the overall thickness of the sample, t₂ is the thickness of each wire/epoxy layer and t₃ is the thickness of the cross-ply 0/90 glass/epoxy layers. For these composites, Equation 4.3 was modified so that it takes into account the wire/epoxy layers. The volume fraction of the components of the composite was replaced by the ratio of the thickness of the 0/90 glass/epoxy composite and the wire layers. Equation 4.4 shows this modification.

\[ E_c = \frac{t_3}{t_1} E_{fm} + \frac{t_2}{t_1} E_{cw0°} + \frac{t_2}{t_1} E_{cw90°} \]  

(4.4)

where \( E_{fm} \) is the Young’s modulus of the cross-ply composite consisting of 0° and 90° plies, both reinforced by glass fibres and \( E_{cw0°} \) and \( E_{cw90°} \) are the Young’s moduli of the layers of wires and matrix in the two different directions.
Figure 4.11 – Sketch of the cross-section of a woven fabric composite with reinforced copper or SMA wires treated as a cross-ply composite.

Now, when the volume fraction, $V_f$, of glass fibre in these composites was measured, it was done so against a total composite volume which includes the outer wire layers. Hence, for the purpose of these calculations, the volume fraction of fibres in the glass-fibres/epoxy layers needs to be increased in the proportion $t_1/t_3$. Hence, $E_{fm}$ is given by:

$$E_{fm} = \frac{1}{2} E_{fm}^0 + \frac{1}{2} E_{fm}^{90^\circ}$$  \hspace{1cm} (4.5)

where $E_{fm}^0$ and $E_{fm}^{90^\circ}$ are given by:

$$E_{fm}^0 = \frac{t_1}{t_3} V_f E_f + \left(1 - V_f \frac{t_1}{t_3}\right) E_m$$  \hspace{1cm} (4.6)

$$\frac{1}{E_{fm}^{90^\circ}} = \frac{t_1}{t_3} V_f + \frac{(1 - V_f \frac{t_1}{t_3})}{E_m}$$  \hspace{1cm} (4.7)

where $V_f$ is the measured fibre volume fraction in the composites.
Chapter 4  

Material properties: Wire properties, reinforcement volume fractions and Young’s modulus of the woven fabric composites

To calculate the Young’s modulus of the composites with reinforcing wires the additional volume of the composite, as a consequence of adding the wires, has been included. The thickness of similar composites, with and without additional wires, was measured and the difference of the average thickness between such composites was taken to be the thickness of the two additional layers of wires plus surrounding matrix. Considering the nominal sample dimension of 15mm × 15mm, and using the measured thicknesses, the volume occupied by the wire layers could then be calculated. For the moduli calculations, the volume fraction of wire is required in those layers and this was calculated by taking into consideration the diameter of the wires (0.152mm), the wire spacing (1.5mm) and the length of the wires in the sample considered (15mm). The volume fraction of wires and matrix in these additional wire/matrix layers can now be found by dividing the volume of the wires by the volume of the layer. Using the volume fractions, the Young’s modulus of the layers with the wires can be calculated using:

\[ E_{cw0^\circ} = V_wE_w + V_mE_m \quad \text{(4.8)} \]

\[ \frac{1}{E_{cw90^\circ}} = \frac{V_w}{E_w} + \frac{V_m}{E_m} \quad \text{(4.9)} \]

where \( V_w \) and \( E_w \) are the volume fraction and the Young’s modulus of the wires. The Young’s modulus of the copper wire was taken to be 120GPa [Comax engineered] and of the SMA wire, 38GPa. \( E_{cw0^\circ} \) and \( E_{cw90^\circ} \) were then used in Equation 4.4 to calculate the Young’s modulus of the overall composite. Table 4.5 shows the predicted values of Young’s modulus of the different types of woven fabric composites based on the volume fraction measurements.

<table>
<thead>
<tr>
<th>No of fabric Layers</th>
<th>Type of composite</th>
<th>with copper wires</th>
<th>with SMA wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>17.7GPa</td>
<td>16.6GPa</td>
<td>15.3GPa</td>
</tr>
<tr>
<td>4</td>
<td>19.6GPa</td>
<td>18.3GPa</td>
<td>18.4GPa</td>
</tr>
<tr>
<td>8</td>
<td>21.9GPa</td>
<td>19.0GPa</td>
<td>19.4GPa</td>
</tr>
</tbody>
</table>

Table 4.5 – Predicted values of Young’s modulus of different types of woven fabric composites.
Comparing the predicted values of the Young’s moduli (Table 4.5) with the measured values (Table 4.4) it can be seen that there is a reasonable agreement. All values agree within 10% except for the four-layer woven fabric composites with SMA wires which show a 15% difference.

4.5 Summary

Samples of the copper and SMA wires used for the impact test were tested and the superelasticity of the SMA wires was investigated. Comparing the two wires it was clearly seen that the SMA wire could undertake much more stress for a given strain than copper and the energy needed to fail the SMA wire was more than four times higher than the energy needed to fail the copper wires.

The volume fraction of the components of the different layers of woven fabric specimens with and without reinforcing copper or SMA wires, was measured by performing a burn-off test on four samples of each type of specimens and the Young’s modulus of each type of composite has been predicted based on these measurements. The composites with wires have been treated as cross-ply composites with two extra layers of wires one for each direction. The measured values of the Young’s modulus for each composite were found by performing tensile test on samples of the composites and the predicted values agreed with the experimental values for all composites within 15%. In the next chapter, the results on eight- and four-layer woven fabric specimens, with and without copper or SMA wires, impacted with single and multiple impact tests are described.
Chapter 5

Impact test results for eight- and four-layer woven fabric composites, with and without copper or SMA wires

5.1 – Introduction

In this Chapter the results for the eight- and four-layer woven fabric composite materials with and without copper or SMA wires will be presented and analysed. Also the results for these types of composite will be compared. From the eight-layer woven composite results presented in this chapter it is possible to determine the impact velocity to be used in the rest of the work and also to establish a methodology for using the video camera appropriately to record the specimens’ penetration. In the next section of the chapter, the number of woven fabric layers was reduced to four layers so that the volume fraction of the wires increase and therefore the effect of the wires would be more obvious. All the eight- and four-layer woven fabric specimens were tested with multiple and single impact tests.

5.2 Impact test results of eight-layer woven fabric composites

As described in Chapter 3, eight-layer woven fabric composite materials with and without copper or SMA wires were impact tested in a servo-hydraulic machine in two different impact experiments, multiple and single impact tests. In some specimens, copper or SMA wires were introduced between the seventh and the eighth layer of the specimens.
5.2.1 Impact test results of eight-layer woven fabric composites without wires

Composite materials with eight-layers of woven fabric without wires were tested at three different speeds, 0.08mmsec\(^{-1}\), 4mmsec\(^{-1}\), and 200mmsec\(^{-1}\) to determine the standard velocity to be used for all the woven fabric specimens.

5.2.1.1 Impact experiments at an impact velocity of 0.08mmsec\(^{-1}\)

Figure 5.1 shows a typical graph of the load-displacement response of a single impact test of an eight-layer woven fabric specimen without wires (W8N.08S-01). The load showed a linear increase as the displacement increased up to 5mm where the slope reduced. After a displacement of 6.5mm where the peak load was reached (3.04kN), the first noticeable decrease of load occurred due to macroscopic crack formation. The first major crack, though, was observed between 6.7mm and 7mm where a sudden drop of load (0.3kN) occurred. Sudden drops of loads due to initiation of penetration during impact test were found by other researchers as well [i.e. Belingardi and Vadori, 2002; Atas and Sayman, 2008; Zhou and Davies, 1995; Shyr and Pan, 2003] The load remained approximately stable until 11mm where it started decreasing as the specimen was penetrated by the impactor, until it reached zero load where full penetration of the specimen had occurred. The overall energy needed for fully penetrating the specimens was found by integrating the load-displacement curve, to be 30J. The method of calculating the energy under the load-displacement curve was already described in Chapter 3.

Other tests showed reasonable reproducibility. Figure 5.2 compares two tests at this impact velocity. There is reasonable agreement between the tests, except for a small difference in the peak load and a small shift in the displacement subsequent to the peak load. The second specimen shown (W8N.08S-03) showed a total energy dissipation of 32J.
Figure 5.1 – Load-displacement response of an eight-layer woven fabric specimen without wires tested with single impact test at an impact velocity of 0.08mmsec\(^{-1}\) (W8N.08S-01).

Figure 5.2 – Load-displacement responses of two eight-layer woven fabric specimens without wires tested with single impact tests at an impact velocity of 0.08mmsec\(^{-1}\) (W8N.08S-01 and W8N.08S-03).

Figure 5.3 shows load-displacement plots for a multiple impact test, starting from the first cycle (Figure 5.3(a)) and adding the next cycle to the next plot (Figures 5.3(b)-5.3(f)) until all seven cycles are added (Figure 5.3(g)) showing a typical load-displacement plot for a multiple impact test on an eight-layer specimen tested at this speed (W8N.08M-02). During these multiple impact tests, seven cycles of impact loading were used and the arrows on Figure 5.3(g) show the load-displacement path followed for each cycle.
Figure 5.3 – Load-displacement responses of an eight-layer woven fabric specimen without wires tested with a multiple impact test at an impact velocity of 0.08 mm/sec\(^{-1}\) (W8N.08M-02), starting from the (a) first cycle and adding the next cycle to the next plot (b)-(f) until (g) all seven cycles are added.
On the first cycle (Figure 5.3(a)), the specimen was loaded to 2mm and then unloaded. The unloading from 2mm displacement is almost linear. For the second cycle (Figure 5.3(b)), the impactor was displaced at 5mm. This time, the unloading curve is offset at zero load, and the area of the hysteresis loop is a measure of the energy dissipated by damage which was found by using the same method as calculating the energy in a single impact test. In the next loading cycle (Figure 5.3(c), to a displacement of 7mm) major damage occurred and a large hysteresis loop is formed. Subsequent cycles were carried out to displacements of 10mm, 12mm, 15mm (Figures 5.3(d)-5.3(f)) and specimen penetration at 18mm (Figure 5.3(g)). For each cycle, the area of the hysteresis was found by the method mention in Chapter 3 and after all seven areas were found, the areas were add-up together to find the overall energy of penetration of the specimen, taking into consideration the overlapping areas between cycles which were subtracted from the overall energy.

Table 5.1 shows the peak loads and the energies of penetration of all the eight-layer woven fabric specimens impacted with single and multiple impact tests at an impact velocity of 0.08mmsec\(^{-1}\). The values are reasonably consistent. Superimposing the multiple impact tests on the eight-layer specimen (e.g. W8N.08M-02) with the single impact test results (e.g. W8N.08S-01) it can be seen that the overall response for the load-displacement graphs is almost identical (Figure 5.4). Using the method mention above for calculating the energy absorbed in the multiple impact test, the overall energy absorbed by the specimen in the multiple impact test (W8N.08-02) was also found to be 30J. The usefulness of the multiple impact tests for determining specimen behaviour will become clearer later.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W8N.08S-01</td>
<td>Single</td>
<td>3.04</td>
<td>30</td>
</tr>
<tr>
<td>W8N.08M-02</td>
<td>Multiple</td>
<td>2.93</td>
<td>30</td>
</tr>
<tr>
<td>W8N.08S-03</td>
<td>Single</td>
<td>3.28</td>
<td>32</td>
</tr>
<tr>
<td>W8N.08M-04</td>
<td>Multiple</td>
<td>3.39</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 5.1 – Peak load and penetration energy of eight-layer woven fabric specimens without wires impacted with single and multiple impact tests at a velocity of 0.08mmsec\(^{-1}\).
Figure 5.4 – Load-displacement responses of eight-layer woven fabric specimens without wires tested with multiple (W8N.08M-02) and single (W8N.08S-01) impact tests at an impact velocity of 0.08mmsec⁻¹.

5.2.1.2 Impact experiments at an impact velocity of 4mmsec⁻¹

A velocity of 0.08mmsec⁻¹ could be achieved on a quasi-static testing machine, but the use of a servo-hydraulic machine enables higher velocities to be used. Eight-layer woven fabric composites were then impact tested at 4mmsec⁻¹. Six specimens were tested at this velocity, three of them using a multiple impact test and the other three using a single impact test. The peak load and the penetration energies of these specimens are shown in Table 5.2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W8N04S-01</td>
<td>Single</td>
<td>3.96</td>
<td>34</td>
</tr>
<tr>
<td>W8N04M-02</td>
<td>Multiple</td>
<td>4.51</td>
<td>37</td>
</tr>
<tr>
<td>W8N04M-03</td>
<td>Multiple</td>
<td>3.77</td>
<td>37</td>
</tr>
<tr>
<td>W8N04S-04</td>
<td>Single</td>
<td>3.61</td>
<td>34</td>
</tr>
<tr>
<td>W8N04S-05</td>
<td>Single</td>
<td>3.23</td>
<td>31</td>
</tr>
<tr>
<td>W8N04M-06</td>
<td>Multiple</td>
<td>3.36</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5.2 – Peak load and penetration energy of eight-layer woven fabric specimens without wires impacted with single and multiple impact tests at an impact velocity of 4mmsec⁻¹.

Figure 5.5 shows the load-displacement responses of the three specimens impacted in single impact tests. The three responses follow the same path and the peak loads and energies of penetrations were reasonably similar (see Table 5.2).
Figure 5.5 – Load-displacement responses of three eight-layer woven fabric specimens without wires tested with single impact tests at an impact velocity of 4mm/sec⁻¹ (W8N04S-01, W8N04S-04 and W8N04S-05).

The advantage of the impact rig designed for use in the servo-hydraulic test machine is the possibility to extract images from the video footage and observe the damage developed during impact. Figure 5.6 shows images from a multiple impact test of an eight-layer woven fabric specimen without wires (W8N04M-03), taken at the displacement of each cycle of a multiple impact test. Figure 5.6 also shows the load-displacement response.

By studying the images in Figure 5.6, the development of damage in the specimen can be seen. Figure 5.6(a) was taken at the maximum displacement of the first loading-unloading cycle (2mm). The impact area can be seen clearly as a white area formed by stress-whitening and microscopic cracks (as will be shown later in the microscopic analysis described in Chapter 9). Figure 5.6(b) taken at the displacement in the second cycle of 5mm shows that the affected area was increased due to more cracks formed in addition to more wide spread stress whitening. Indeed cracks could be heard forming during this cycle of the impact experiment. At 8mm displacement, just after the sudden drop of the load, Figure 5.6(c) was taken. It is believed that the first macroscopic crack was formed during this cycle which is why there is this sudden drop of load. Although the crack cannot be seen clearly at this stage, the fibres starting to fail and a cross shape is forming. Figures 5.6(d)-(g) show the gradual penetration of the specimen appear to be by the impactor from 10mm (Figure 5.6(d)) to 18mm...
Impact results of eight- and four-layer woven fabric specimens with and without copper or SMA wires (Figure 5.6(g)). The images show the failure of the fibres in the shape of a cross (Figure 5.6(d) and (e)), progressing to visibility of the impactor (Figure 5.6(f) and (g)). Figure 5.6(h) is an image of the impact area of the specimen after the experiment was complete.

Figure 5.6 - Load-displacement response of an eight-layer woven fabric specimen without wires (W8N04M-03) tested with multiple impact test, at an impact velocity of 4mmsec⁻¹, with images at the maximum displacement of each cycle of the test.

Figure 5.7 shows a single impact tested specimen without wires (W8N04S-04), with images taken during impact at the equivalent displacements as for the multiple impact specimen above (W8N04M-03). A similar development of damage can be seen in the single impact specimen including that, in addition to the similarity in overall load-displacement and energy absorption, damage development is also very similar for the multiple and single impact tests.
Figure 5.7 - Load-displacement response of an eight-layer woven fabric specimen without wires (W8N04S-04) tested with single impact test at an impact velocity of 4mmsec^{-1} with images taken at the maximum displacement for each cycle as used in the multiple impact tests.

5.2.1.3 Impact experiments at a speed of 200mmsec^{-1}

Figure 5.8 shows a characteristic load-displacement response of a single impact test of an eight-layer woven fabric specimen without wires (W8N200S-01) tested at the highest impact velocity used 200mmsec^{-1}. The vibrations created by the impact produce a somewhat noisy response. Despite this, the usual trend seen can be identified, with load increasing at low displacement and experience a load drop after the peak load in this case, (4.66kN) at around 8mm displacement and then the load gradually decreases to zero as the displacement increases. The overall energy needed to penetrate the specimen was found from the area under the load-displacement graph to be 41J. To find the energy with a noisy response, it was necessary to ignore the unloading part of the cycle from 18mm in the measurement of area (this is normally zero load anyway).
Impact results of eight- and four-layer woven fabric specimens with and without copper or SMA wires

Figure 5.8 – Load-displacement response of an eight-layer woven fabric specimen without wires tested with single impact test at an impact velocity of 200mm/sec\(^{-1}\) (W8N200S-01).

5.2.1.4 Choosing the standard impact velocity

To choose the standard velocity to be used in subsequent impact experiments, a comparison is shown in Figure 5.9 of the load-displacement response of specimens impacted with single impact tests for three velocities.

Figure 5.9 – Load-displacement responses of eight-layer woven fabric specimens without wires tested with single impact tests at 0.08mm/sec\(^{-1}\) (W8N0.08S-03), at 4mm/sec\(^{-1}\) (W8N04S-04) and at 200mm/sec\(^{-1}\) (W8N200S-01).

It is interesting to note a possible strain-rate effect in these results, with the peak load increasing with velocity. The velocity of the 4mm/sec\(^{-1}\) was chosen to be the standard velocity used since the higher velocity (200mm/sec\(^{-1}\)) produced unwanted vibrations...
and the lower velocity 0.08mmsec\(^{-1}\) could be achieved in a quasi-static testing machine.

### 5.2.2 Impact test results of eight-layer woven fabric composites with copper wires

In the previous section, the impact velocity for the tests was established and it was then necessary to determine the appropriate SMA wire volume fraction for the bulk of the tests. The SMA wire is very expensive compared to copper wire, and hence tests were carried out using the copper wire initially to investigate the wire volume fraction effects. As described in Chapter 3, some of the eight-layer woven fabric specimens were tested with three different volume fractions of copper wires, with the copper wires introduced between the seventh and eighth layer of the woven fabric layers. The volume fraction of the copper wires was between 0.003-0.01. Figure 5.10 shows the results of load – displacement plot of multiple and a single impact tests for two specimens with 0.003 volume fraction of copper wires.

![Figure 5.10 - Load-displacement responses of eight-layer woven fabric specimens with low Vf of copper wires (Vf=0.003) tested with multiple (W8C04M-01L) and a single (W8C04S-02L) impact tests.](image)

The overall load-displacement response of multiple impact test is almost identical to the response of the single impact test, as was seen with specimens without wires. The specimens have similar peak loads (4.23kN for W8C04M-01L and 4.1kN for W8C04S-02L) with the peak load occurring at approximately at the same
displacement. Also, the sudden drop of load happened at roughly the same displacement. The energy needed to penetrate the specimens was 34J for W8C04M-01L and 38J for W8C04S-02L.

Comparison of the single impact test specimen with low volume fraction of copper wires (W8C04S-02L) with the single impact test specimen without any wires (W8N04S-01) it can be seen that the load-displacement response (Figure 5.11) is very similar. Hence, two further volume fractions of copper wire were tested; 0.006 and 0.01.

Figure 5.11 – Load-displacement responses of eight-layer woven fabric specimens without wires (W8N04S-01) and with low V_f of copper wires (W8C04S-02L), impacted with single impact tests.

Figure 5.12 and Figure 5.13 show single and multiple impact tests for copper wire volume fractions of 0.006 and 0.001, respectively. The results for V_f=0.006 are very similar to V_f=0.003, whereas the results for V_f=0.01 show an enhanced peak load and the energy for penetration.

Table 5.3 shows the peak loads and the penetration energies of all the eight-layer woven fabric specimens with different volume fractions of copper wires impacted with multiple and single impact tests. The first specimen on the table shows the results of an eight-layer woven fabric specimen without wires so a comparison for eight-layer composites without copper wires and with the three volume fractions tested can be
made. The highest volume fraction of copper wire shows a clear difference, which is obvious when the curves of the single impacted specimens with and without copper wires were compared in Figure 5.14. Hence, this volume fraction was chosen for the initial work with the SMA wires.

**Figure 5.12** – Load-displacement responses of a multiple (W8C04M-03M) and of a single (W8C04S-04M) impact test of eight-layer woven fabric specimens with medium $V_f$ of copper wires ($V_f=0.06$).

**Figure 5.13** – Load-displacement responses of a multiple (W8C04M-05H) and of a single (W8C04S-06H) impact test of eight-layer woven fabric specimens with high $V_f$ of copper wires ($V_f=0.01$).
Table 5.3 – Peak load and penetration energy of eight-layer woven fabric specimens with three different volume fractions of copper wires impacted with single and multiple impact tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Vf of copper wires</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W8N04S-01</td>
<td>Single</td>
<td>0</td>
<td>3.96</td>
<td>34</td>
</tr>
<tr>
<td>W8C04M-01L</td>
<td>Multiple</td>
<td>0.003</td>
<td>4.23</td>
<td>34</td>
</tr>
<tr>
<td>W8C04S-02L</td>
<td>Single</td>
<td>0.003</td>
<td>4.1</td>
<td>38</td>
</tr>
<tr>
<td>W8C04M-03M</td>
<td>Multiple</td>
<td>0.006</td>
<td>4.34</td>
<td>37</td>
</tr>
<tr>
<td>W8C04S-04M</td>
<td>Single</td>
<td>0.006</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>W8C04M-05H</td>
<td>Multiple</td>
<td>0.01</td>
<td>4.54</td>
<td>41</td>
</tr>
<tr>
<td>W8C04S-06H</td>
<td>Single</td>
<td>0.01</td>
<td>4.51</td>
<td>40</td>
</tr>
<tr>
<td>W8C04M-07H</td>
<td>Multiple</td>
<td>0.01</td>
<td>4.71</td>
<td>41</td>
</tr>
</tbody>
</table>

Figure 5.14 – Load-displacement responses of eight-layer woven fabric specimens without wires (W8N04S-01), with low Vf of copper wires (W8C04S-02L), with medium Vf of copper wires (W8C04S-04M) and with high Vf of copper wires (W8C04S-06H), impacted with single impact tests.

5.2.3 Impact test results of eight-layer woven fabric composites with SMA wires

Shape-memory alloy (SMA) wires were introduced within eight-layer woven fabric specimens, between the seventh and eighth layer. The volume fraction of the wires was normally 0.01, though burn-off tests shown that the volume fraction to be in a range of 0.008-0.009. Multiple and single impact experiments were undertaken, at an impact velocity of 4mm/sec⁻¹.
Figure 5.15 shows the results of two specimens with SMA wires; one tested with multiple impact (W8S04M-01) and the other one with a single impact (W8S04S-02). As seen with specimens with and without copper wires previously, the load-displacement plots of the multiple and single impact experiments are very similar (peak loads of 4.25kN and 4.27kN and penetration energies of 37J and 38J, respectively). The discontinuities in the load-displacement plot suggest that some form of damage is occurring before the peak load (this is investigated further in Chapters 8 and 9). Table 5.4 shows the peak loads and penetration energies of all the eight-layer woven fabric specimens with SMA wires impacted with multiple and single impact tests.

![Load-displacement plot](image)

**Figure 5.15 – Load-displacement responses of a multiple (W8S04M-01) and of a single (W8S04S-02) impact test of eight-layer woven fabric specimens with SMA wires.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W8S04M-01</td>
<td>Multiple</td>
<td>4.25</td>
<td>37</td>
</tr>
<tr>
<td>W8S04S-02</td>
<td>Single</td>
<td>4.27</td>
<td>38</td>
</tr>
<tr>
<td>W8S04S-03</td>
<td>Single</td>
<td>4.48</td>
<td>39</td>
</tr>
<tr>
<td>W8S04M-04</td>
<td>Multiple</td>
<td>4.41</td>
<td>38</td>
</tr>
</tbody>
</table>

**Table 5.4 – Peak load and penetration energy of eight-layer woven fabric specimens with SMA wires impacted with single and multiple impact tests.**

Images were extracted from the video record of the multiple impact test. Figure 5.16 shows images for a multiple impact test. A damage area is noticeable on the first
cycle (Figure 5.16(a)), indicated by a whitened area. The damage area increased in the second cycle (Figure 5.16(b)) and a small crack is visible. In the third cycle (Figure 5.16(c)) crack is clearly visible (after a large drop in load). This crack extends through subsequent cycles.

Figure 5.16 - Load-displacement response of a multiple impact test of an eight-layer woven fabric specimen with SAIA wires (W8S04M-01) with images at the maximum displacement for each cycle of the test.

5.2.4 Comparison of the results of impact testing for eight-layer woven fabric composites with and without wires

Figure 5.17 shows a comparison of the load-displacement response of three specimens: without wires (W8N04S-01), with copper wires (W8C04S-06H) and with...
SMA wires (W8S04S-03), impacted with single impact test, where the SMA and copper wire volume fractions were the same (V_f=0.01).

![Graph showing load-displacement responses](image)

Figure 5.17 – Load-displacement responses of eight-layer woven fabric specimens without wires (W8N04S-01), with high V_f of copper wires (W8C04S-06H) and with SMA wires (W8S04S-03), impacted with single impact tests.

All three specimens started with very similar stiffness but the peak loads of the specimens with wires were higher than the specimen without wires. No difference can be seen between the behaviour of the specimens with SMA or copper wire. To investigate any possible differences the number of the layers of woven fabric was reduced from eight to four (so that the volume fraction of the wires will increase). These results are presented in the next sections.

### 5.3 Impact test results of four-layer woven fabric composites

To investigate the effect of the SMA wires, the number of woven fabric layer was reduced to four and tested with multiple and single impact test. Some of the specimens were reinforced with copper or SMA wires, between the third and the forth layer of the specimens.
5.3.1 Impact test results of four-layer woven fabric composites without wires

Four specimens with four-layer woven fabric without wires were impacted, two with multiple impact test and two with single impact test method. Table 5.5 shows the peak loads and the penetration energies of these four specimens. The values are close to each other with an exception the values of specimen W4N04S-04 which are a bit higher than the rest but in an accepted range.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W4N04M-01</td>
<td>Multiple</td>
<td>1.94</td>
<td>12</td>
</tr>
<tr>
<td>W4N04S-02</td>
<td>Single</td>
<td>1.99</td>
<td>13</td>
</tr>
<tr>
<td>W4N04M-03</td>
<td>Multiple</td>
<td>2.17</td>
<td>14</td>
</tr>
<tr>
<td>W4N04S-04</td>
<td>Single</td>
<td>3.37</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.5 – Peak load and penetration energy of four-layer woven fabric specimens without wires impacted with single and multiple impact tests.

Figure 5.18 shows the load-displacement response of two specimens impacted in a single impact test. Although that one of specimen has a higher peak load and penetration energy, due to this higher peak load, than the other specimen the trail response is very similar.

Figure 5.18 – Load-displacement responses of two four-layer woven fabric specimens without wires tested with single impact tests (W4N04S-02 and W4N04S-04).
Figure 5.19 shows the load-displacement of two specimens of four-layer woven fabric without wires, one impacted with multiple impact test (W4N04M-01) and the other one with single impact test (W4N04S-02). Both specimens have a similar behaviour with specimen W4N04S-02 having a slightly higher stiffness and peak load which occurred at a lower displacement than for W4N04M-01. The sudden drop is higher for W4N04S-02 (0.5kN) than for W4N04M-01 (0.4kN) and it took place at a lower displacement as well. The overall energy of penetration was 13J for W4N04S-02 slightly higher than W4N04M-01 which it was 12J.

![Load-displacement response graphs](image)

*Figure 5.19 – Load-displacement responses of a multiple (W4N04M-01) and of a single (W4N04S-02) impact test of four-layer woven fabric specimens without wires.*

Images were extracted from the video footages of the four-layer woven fabric specimens as well. Figure 5.20 shows pictures from a multiple impact test of a four-layer woven fabric specimen without wires (W4N04M-03), taken at the maximum displacement of each cycle a multiple impact test and the equivalent load-displacement response.

By examining the images of Figure 5.20, the damage growth can be seen. The first image (Figure 5.20(a)) shows the specimen impacted to 2mm in displacement. No apparent damage was shown and the impactor can be identified on the image due to the fact that the specimen contains less layers of woven fabric which makes it more transparent. The damage started developing in the second image (Figure 5.20(b)) which was taken at 5mm in displacement and increase in Figure 5.20(c) which was
taken at 8mm inside the specimen. The first macroscopic crack can be identified on the Figure 5.20(d) as a black dot in the middle of the impacted area and the damage around the impact area continues to increase. Figures 5.20(e) to 5.20(g) shows the penetration of the specimen by the impactor and Figure 5.20(h) shows the specimen after impact.

![Macroscopic crack](image)

**Figure 5.20** – Load-displacement response of a multiple impact test of a four-layer woven fabric specimen without wires (W4N04M-03) with images at the maximum displacement of each cycle of the test.

Figure 5.21 shows pictures from a single impact test of a four-layer woven fabric specimen without wires (W4N04-04), taken at the maximum displacement of each cycle of a multiple impact test and the load-displacement response. The images were extracted for the equivalent displacements of the multiple impact tested specimen above (W4N04M-03). The overall sequence of damage development for the single
impact tested specimen was very similar to the sequence for the multiple impact tested specimen. Hence, both the four- and eight-layer laminates show no apparent difference in damage development between single and multiple impact tests.

Figure 5.21 - Load-displacement response of a single impact test of a four-layer woven fabric specimen without wires (W4N04S-04) with images taken at the maximum displacement for each cycle used in the multiple impact tests.

5.3.2 Impact test results of four-layer woven fabric composites with copper wires

Copper wires were inserted in the four-layer woven fabric specimens and impact tested as well. The volume fraction of the copper wires in the four-layer woven fabric specimens was around 0.02. Figure 5.22 shows the load-displacement response of three four-layer woven fabric specimens with reinforcing copper wires. The three responses are almost identical with very close peak loads and energies of penetration.
Figure 5.23 shows the load-displacement response of multiple and single impact tests of four-layer woven fabric specimens with copper wires. As it was already seen before, the specimens had a very similar load displacement plot with the same stiffness with a slightly higher peak load for the specimen impacted with single impact test (W4C04S-02) than the specimen impacted with single impact test (W4C04M-01). The overall energies for penetrating the specimens were close as well.

Figure 5.22 – Load-displacement responses of three four-layer woven fabric specimens with copper wires tested with single impact tests (W4C04S-02, W4C04S-03 and W4C04S-05).

Figure 5.23 – Load-displacement responses of a multiple (W4C04M-01) and a single (W4C04S-02) impact test of four-layer woven fabric specimens with copper wires.
Chapter 5  Impact results of eight- and four-layer woven fabric specimens with and without copper or SMA wires

Table 5.6 shows the peak loads and the penetration energies of all four-layer woven fabric specimens with copper wires impacted with single or multiple impact tests. The values are consistent.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of Impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W4C04M-01</td>
<td>Multiple</td>
<td>1.69</td>
<td>14</td>
</tr>
<tr>
<td>W4C04S-02</td>
<td>Single</td>
<td>1.93</td>
<td>15</td>
</tr>
<tr>
<td>W4C04S-03</td>
<td>Single</td>
<td>2.04</td>
<td>15</td>
</tr>
<tr>
<td>W4C04M-04</td>
<td>Multiple</td>
<td>1.77</td>
<td>15</td>
</tr>
<tr>
<td>W4C04S-05</td>
<td>Single</td>
<td>1.89</td>
<td>16</td>
</tr>
<tr>
<td>W4C04M-06</td>
<td>Multiple</td>
<td>1.97</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.6 - Peak load and penetration energy of four-layer woven fabric specimens with copper wires impacted with single and multiple impact tests.

5.3.3 Impact test results of four-layer woven fabric composites with SMA wires

The copper wires were replaced with SMA wires in the four-layer woven fabric specimens with the same volume fraction as the specimens with copper wires (0.02). Figure 5.24 shows the load-displacement response of two specimens of four-layer woven fabric specimens with SMA wires. The two responses are very similar even though one of them has a slightly higher peak load than the other one.

Specimens were impacted using the multiple and single impact test methods. Figure 5.25 shows the comparison between a specimen tested with a multiple impact test (W4S04M-01) and a specimen tested with a single impact test (W4S04S-02). Once again the paths of the two specimens were very similar. Specimen W4S04S-02 had a higher peak load than specimen W4S04M-01 and a higher sudden drop load (0.6kN) which for specimen W4S04M-01 is almost non-existed (0.3kN). The overall energies needed to penetrate the specimens were similar as well. Table 5.7 shows the values of the peak load and penetration energies of all four-layer woven fabric specimens with SMA wires impacted with multiple and single impact tests.

Figure 5.26 shows the load-displacement plot of a four-layer woven fabric specimen with SMA wires (W4S04M-01) impacted with multiple impact test and a sequence of
images extracted at the maximum displacement of each cycle. The wires appear as black lines in the figures in almost all the images because fewer numbers of layers used in these specimen makes them more transparent. In the first cycle of the multiple impact test, no damage occurs on a macroscopic level (Figure 5.26(a)). A combination of matrix cracks and delaminations are formed during the second cycle (Figure 5.26(b)) which appears as a whitened area in the image. The penetration of the specimen start at the third cycle (Figure 5.26(c)) and it is even clearer in the fourth one (Figure 5.26(d)) where a macroscopic through-thickness crack starts appearing on the specimen in the shape of a line. The crack is increasingly visible in the later images (Figure 5.26(e) to 5.26(g)) as the impactor penetrates the specimen. Figure 5.26(h) is an image of the specimen after impact.

Figure 5.24 – Load-displacement responses of two four-layer woven fabric specimens with SMA wires tested with single impact tests (W4S04S-02 and W4S04S-03).

Figure 5.25 – Load-displacement responses of a multiple (W4S04M-01) and a single (W4S04S-02) impact test of four-layer woven fabric specimens with SMA wires.
Chapter 5

Impact results of eight- and four-layer woven fabric specimens with and without copper or SMA wires

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of Impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W4S04M-01</td>
<td>Multiple</td>
<td>2.11</td>
<td>15</td>
</tr>
<tr>
<td>W4S04S-02</td>
<td>Single</td>
<td>2.37</td>
<td>16</td>
</tr>
<tr>
<td>W4S04S-03</td>
<td>Single</td>
<td>2.17</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.7 – Peak loads and penetration energies of four-layer woven fabric specimens with SMA wires impacted with single and multiple impact tests.

5.3.4 Comparing the results of impact testing for four-layer woven fabric composites with and without copper or SMA wires

Comparing the four-layer woven fabric specimens with and without copper or SMA wires, the effect of the wires can be recognised. Figure 5.27 shows this comparison.
between specimen W4N04S-02, without wires, specimen W4C04S-03, with copper wires, and specimen W4S04S-02, with SMA wires, all tested with single impact tests.

![Graph showing load-displacement responses](image)

**Figure 5.27 – Load-displacement responses of four-layer woven fabric specimens without wires (W4N04S-02), with copper wires (W4C04S-03) and with SMA wires (W4S04S-02) tested with single impact tests.**

The load in all specimens increase in the same rate as the displacement up to about 7mm were the formation of cracks start to appear. Specimen W4N04S-02 (without wires) reached its peak load at an earlier displacement than the other specimens and specimen W4S04S-02 (with SMA wires) had a much higher peak load than the other two specimens which it occurred at a higher displacement. Although the peak load and the sudden drop (0.6kN for W4C04S-03, 0.45kN for W4N04S-02) of the specimens had very close values, the effect of the SMA wires can be seen after the sudden drop where the values of load for specimen W4S04S-02 were kept higher than the ones of specimens W4N04S-02 and W4C04S-03 at the same displacement. After the sudden drop the load, the load decreases at a similar rate up to the point of full penetration were the specimens were fully penetrated. For specimens W4S04S-02 and W4N04S-02 that point was around 17mm were as for specimen W4C04S-03 was at around 18mm. Specimen W4S04S-02 needed slightly more energy to be fully penetrated than specimen W4C04S-03. Specimen W4N04S-02 needed the least energy to be penetrated.
5.4 Comparing the results of impact testing for eight-layer and four-layer woven fabric composites with and without copper or SMA wires

A brief comparison of the results of the impact testing for eight- and four-layer woven fabric with and without copper or SMA wires is presented here; a full comparison between these composites and also between the two-layer woven fabric specimens with and without copper or SMA wires is made at the end of Chapter 6. Figure 5.28 shows the load-displacement response of six specimens impacted using the single impact test. The specimens are eight-layer woven fabric without wires (W8N04S-01), with copper wires (W8C04S-06H) and with SMA wires (W8S04S-03); and four-layers of woven fabric without wires (W4N04S-02), with copper wires (W4C04S-03) and with SMA wires (W4S04S-02). The increase of load is reasonably linear during the impact test for the eight-layer woven fabric specimens whereas for the four-layer woven fabric specimens it is non-linear. Table 5.8 shows the average values of the peak load and the penetration energy for the eight- and four-layer woven fabric specimens with and without copper or SMA wires, tested with single and multiple impact tests.

Comparing the average values of peak load and energy for the eight-layer woven fabric composites with and without copper or SMA wires, no significant increase was found by adding the SMA wires. On the contrary, overall, composites with copper wires showed a bigger increase in peak load and energy absorbed than composites with SMA wires. Looking at the average values of peak load of the four-layer woven fabric composites with and without copper or SMA wires, it can be seen that composite without wires have the higher peak loads. Also, the increase in energy absorbed by composites without wires compared to composites with wires is about the same for composites with copper and composites with SMA wires. To investigate any beneficial effect of the SMA wires on composite response to impact, it seems clear that the wire volume fraction should be increased. Consequently, the layers of woven fabric were reduced further to two layers.
Impact results of eight- and four-layer woven fabric specimens with and without copper or SMA wires

Figure 5.28 – Load-displacement response of six specimens impacted with single impact test, with eight-layer of woven fabric without wires (W8N04S-01), with copper wires (W8C04S-06H) and with SMA wires (W8S04S-03) and with four-layer of woven fabric without wires (W4N04S-02), copper wires (W4C04S-03) and SMA wires (W4S04S-02).

<table>
<thead>
<tr>
<th>Type of Specimen</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
<th>Average thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight-layer woven fabric specimens without wires</td>
<td>3.7±0.5</td>
<td>34±3</td>
<td>2.7±0.1</td>
</tr>
<tr>
<td>Eight-layer woven fabric specimens with copper wires</td>
<td>4.6±0.1</td>
<td>40.7±0.6</td>
<td>2.81±0.05</td>
</tr>
<tr>
<td>Eight-layer woven fabric specimens with SMA wires</td>
<td>4.35±0.09</td>
<td>38±0.8</td>
<td>2.93±0.04</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens without wires</td>
<td>2.4±0.7</td>
<td>14±1</td>
<td>1.43±0.05</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens with copper wires</td>
<td>1.9±0.1</td>
<td>15.0±0.6</td>
<td>1.71±0.04</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens with SMA wires</td>
<td>2.2±0.1</td>
<td>15.3±0.6</td>
<td>1.60±0.02</td>
</tr>
</tbody>
</table>

Table 5.8 – Average values of the peak load, penetration energy and thickness for the eight- and four-layer woven fabric specimens with and without copper or SMA wires tested with single and multiple impact tests.

5.5 Summary

In this chapter, the methods used for the impact tests, and the types of specimens used, have been described. Eight-layer woven fabric specimens without wires were tested at three different velocities so the optimum velocity for subsequent experiments could be found; this was determined to be 4mmsec⁻¹. Eight-layer woven fabric specimens with three different volume fractions of copper wires, in the range of 0.003-0.01, were impact tested at this velocity and it was found that only the specimens with a high volume fraction of wires (Vf=0.01) showed a significant effect.
Consequently, eight-layer woven fabric specimens with and without copper or SMA wires with a volume fraction of 0.01 were impacted at 4mmsec$^{-1}$ and compared. The specimens with copper or SMA wires showed improved impact properties over the specimens without wires. However there were no major differences found between the results for SMA and copper wire and therefore it was decided to increase the volume fraction of the wires overall by decreasing the number of layers of woven fabric to four.

Four-layer woven fabric specimens, with and without reinforcing copper or SMA wires with 0.02 volume fraction were impacted at 4mmsec$^{-1}$ and analysed. The four-layer specimens with reinforcing SMA wires showed improved energy absorption over the four-layer woven fabric specimens without wires but still the effect of the wires is not clear. On the basic of these results, it was decided to investigate the effect of the SMA wires by decreasing the number of layers to two layers so the volume fraction of the SMA wires is increased further more. Most of the impact experiments were carried out with two-layer composites and these results are described in the next chapter (Chapter 6).
Chapter 6

Impact test results for two-layer woven fabric composites, with and without copper or SMA wires

6.1 Introduction

The number of woven fabric layers was reduced to two layers so that the volume fraction of the wires was increased even more than four-layer specimens and therefore the effect of copper or SMA wires would be more obvious. The copper or SMA wires were introduced between the two layers of woven fabric of the specimens. The specimens were tested with multiple, single and partial penetration impact tests at a speed of 4mmsec\(^{-1}\). In this chapter the results for the two-layer woven fabric composite materials with and without copper or SMA wires tested will be presented and analysed. Furthermore, the results from multiple, single and partial penetration impact tests will be compared between them and also the results of the two layer woven fabric specimens with and without copper or SMA wires will be compared with the equivalent specimen type of eight-layer and four-layer woven fabric that was analysed in Chapter 5.

6.2 Single and multiple impact test results of two-layer woven fabric composites without wires

Six specimens without wires were tested; three of them using single impact test and the other three using multiple impact test. The peak loads and the penetration energies of these specimens are shown in Table 6.1. The peak loads and the penetration energies of the specimens are reasonably consistent results for both multiple and
single impact test. Figure 6.1 shows the load-displacement response of the three specimens tested with single impact test. The results are almost identical. The load of the specimens increase as the displacement increase, with the same rate, up to around 1kN where the peak load occurs and right after that the sudden drop of load occurred, indicating the initiation of penetration, as its already seen in eight- and four-layer in the previous chapter and in the literature [i.e. Belingardi and Vadori, 2002; Atas and Sayman, 2008; Zhou and Davies, 1995; Shyr and Pan, 2003]. After that the load of the specimens decreases to zero, as the specimens were fully penetrated by the impactor.

![Table 6.1](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of Impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2N04M-01</td>
<td>Multiple</td>
<td>1.09</td>
<td>5.4</td>
</tr>
<tr>
<td>W2N04S-02</td>
<td>Single</td>
<td>1.02</td>
<td>5.7</td>
</tr>
<tr>
<td>W2N04M-03</td>
<td>Multiple</td>
<td>1.15</td>
<td>5.5</td>
</tr>
<tr>
<td>W2N04S-04</td>
<td>Single</td>
<td>1.01</td>
<td>5.4</td>
</tr>
<tr>
<td>W2N04S-05</td>
<td>Single</td>
<td>1.04</td>
<td>6.2</td>
</tr>
<tr>
<td>W2N04M-06</td>
<td>Multiple</td>
<td>0.96</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 6.1 – Peak load and penetration energy of two-layer woven fabric specimens without wires impacted with single and multiple impact tests.

Figure 6.1 – Load-displacement response of three two-layer woven fabric specimens without wires tested with single impact test (W2N04S-02, W2N04S-04 and W2N04S-05).

Figure 6.2 shows the load-displacement response of two two-layer woven fabric specimens without wires tested with multiple impact (W2N04M-01) and single
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Impact results of two-layer woven fabric specimens with and without copper or SMA wires

Impact (W2N04S-02) tests. Two-layer woven fabric specimens also give similar responses when impacted with the two different types of impact tests.

Figure 6.2 – Load-displacement responses of two-layer woven fabric specimens without wires tested with multiple (W2N04M-01) and single (W2N04S-02) impact tests.

Figure 6.3 shows the images extracted from the video footage of a multiple impact test of a two-layer woven fabric specimen without wires (W2N04M-03), taken at the maximum displacement of each cycle of the multiple impact test. By studying the pictures the development of damage in the specimen can be seen. Figure 6.3(a) was taken at the maximum displacement of the first cycle (2mm). No obvious damage on the specimen can be seen on that picture, but, as it will be shown in Chapter 9 later, microscopic matrix cracks are formed on the specimen even when impacted on such a low displacement. The impactor can be clearly identified in the picture and so as the two directions of the fibres. The damage started to be obvious by visual inspection, at the second picture (Figure 6.3(b)) which was taken at the maximum displacement of the second cycle (5mm), as a white area formed by stress-whitening and microscopic cracks. The impactor can be still identified in this picture as well. The damage area increased at the maximum displacement of the third cycle (8mm) as shown in Figure 6.3(c). Figures 6.3(d)-(g) show the gradual penetration of the specimen by the impactor from 10mm (Figure 6.3(d)) to 18mm (Figure 6.3(g)) and the failure of the fibres in the shape of a cross which is more obvious in Figure 6.3(e). Figure 6.3(h)
shows a picture of the impact area of the specimen after the experiment was complete. A more detailed discussion of the damage development can be found in Chapters 8-9.

Figure 6.3 - Load-displacement response of a two-layer woven fabric specimen without wires (W2N04M-03) tested with multiple impact test, with images at the maximum displacement of each cycle of the test.

Figure 6.4 shows a single impact tested specimen without wires (W2N04S-04), with images taken during impact at the equivalent displacements as for the multiple impact specimen above (W2N04M-03). In addition to the similarity in overall load-displacement and energy absorption, the sequence of damage development of the single impact specimen is very similar with the sequence of damage development of the multiple impact specimen (W4N04M-03), even though the failure of the fibres in a shape of a cross is not so clear in the single impact specimen (Figure 6.4(e)).
6.3 Single and multiple impact test results of two-layer woven fabric composites with copper wires

Some of the two-layer woven fabric specimens were introduced with copper wires between the two layers of woven fabric. The volume fraction of the wires in the specimens was around 0.03, as was measured by burn-off tests that were presented in Chapter 4. Figure 6.5 shows the load-displacement response of two two-layer woven fabric specimens with copper wires tested with single impact tests. The response of the wires was almost identical as it was seen with the specimens without wires above as well, with very close values of peak loads and energies of penetration. As noted previously, the discontinuities in the load-displacement plot suggest that some form of damage is occurring before the peak load (this is investigated further in Chapters 8 and 9). Table 6.2 shows the peak loads and the penetration energies of all two-layer
woven fabric specimens with copper wires impacted with single and multiple impact tests. The values are consistent.

![Load-displacement response](image)

Figure 6.5 – Load-displacement response of two two-layer woven fabric specimens with copper wires tested with single impact test (W2C04S-02 and W2C04S-03).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2C04M-01</td>
<td>Multiple</td>
<td>1.1</td>
<td>6.2</td>
</tr>
<tr>
<td>W2C04S-02</td>
<td>Single</td>
<td>1.16</td>
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<tr>
<td>W2C04M-05</td>
<td>Multiple</td>
<td>1.14</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 6.2 – Peak load and penetration energy of two-layer woven fabric specimens with copper wires impacted with single and multiple impact tests.

Figure 6.6 shows the load-displacement response of multiple and single impact tests of two-layer woven fabric specimens with copper wires. Single impact specimen, (W2C04S-02) was slightly stiffer than the multiple impact specimen (W2C04M-01) and had a slightly higher peak which took place at the same displacement at around 8mm. The load values of the fifth cycle of the multiple impact test was a bit higher than the load values of the single impact specimen at the same displacement but did not affect the energy of penetration which was almost identical for the two specimens (see Table 6.2). Both the specimens were fully penetrated at around 16mm in displacement.
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Figure 6.6 - Load-displacement responses of two-layer woven fabric specimens without wires tested with multiple (W2C04M-01) and single (W2C04S-02) impact tests.

6.4 Single and multiple impact test results of two-layer woven fabric composites with SMA wires

The copper wires were replaced by SMA wires between the two layers of woven fabric specimens as it happen with eight-layer and four-layer woven fabric specimens. Burn off tests on the specimens showed that the volume fraction of the wires was around 0.024. Nine two-layer woven fabric specimens with SMA wires were tested; five specimens were tested using multiple impact tests and four using single impact tests. Figure 6.7 shows the load-displacement response of four specimens of two-layer woven fabric specimens with SMA wires. Once again the results are very similar to each other proving the reproducibility of the data during the experiments.

Figure 6.7 - Load-displacement response of four two-layer woven fabric specimens with SMA wires tested with single impact test (W2N04S-02, W2N04S-03, W2N04S-05 and W2S04S-06).
Figure 6.8 shows load-displacement response of two two-layer woven fabric specimens with SMA, one tested with multiple impact test (W2S04M-09) and the other one with single impact test (W2S04S-05). The specimens with SMA wires have very similar load-displacement responses as well.

![Load-displacement response of two-layer woven fabric specimens with SMA wires](image)

Figure 6.8 – Load-displacement response of a multiple (W2S04M-09) and a single (W2S04S-06) impact test of two-layer woven fabric specimens with SMA wires.

Table 6.3 shows the peak loads and the penetration energies of all the two layer-woven fabric specimens with SMA wires. The values are reasonable consistent.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Method of impact</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2S04M-01</td>
<td>Multiple</td>
<td>1.24</td>
<td>7.3</td>
</tr>
<tr>
<td>W2S04S-02</td>
<td>Single</td>
<td>1.2</td>
<td>7.7</td>
</tr>
<tr>
<td>W2S04S-03</td>
<td>Single</td>
<td>1.27</td>
<td>7.8</td>
</tr>
<tr>
<td>W2S04M-04</td>
<td>Multiple</td>
<td>1.05</td>
<td>7.4</td>
</tr>
<tr>
<td>W2S04S-05</td>
<td>Single</td>
<td>1.16</td>
<td>7.2</td>
</tr>
<tr>
<td>W2S04S-06</td>
<td>Single</td>
<td>1.13</td>
<td>7.1</td>
</tr>
<tr>
<td>W2S04M-07</td>
<td>Multiple</td>
<td>1.08</td>
<td>7.4</td>
</tr>
<tr>
<td>W2S04M-08</td>
<td>Multiple</td>
<td>1.24</td>
<td>6.9</td>
</tr>
<tr>
<td>W2S04M-09</td>
<td>Multiple</td>
<td>1.12</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 6.3 – Peak load and penetration energy of two-layer woven fabric specimens with SMA wires impacted with single and multiple impact tests.

Figure 6.9 shows the load-displacement plot of a two layer woven fabric specimen with SMA wires (W2S04M-04) tested using multiple impact test and images from the
maximum displacement of each cycle. The SMA wires are visible in almost all the images as well. In the first cycle (Figure 6.9(a)) the impactor can be identified and no damage can be detected but microscopic cracks were formed as will be shown in the microscopic analysis of the two-layer woven fabric specimens which is presented in Chapter 9. The damage could be seen, by visual inspection on the second cycle of the impact test (Figure 6.9(b)) where the impactor is still visible. The damage is in the form of a white area created by stress-whitening and microscopic cracks. The first macroscopic crack can be seen in the third cycle (Figure 6.9(c)) in the middle of the impact area as a black dot. The initiation of penetration of the specimen is more obvious in the forth cycle (Figure 6.9(d)) where fibre fractures are visible. Figures 6.9(e)-6.9(g) shows the impactor penetrating the specimen. Figure 6.9(h) shows an image of the penetrated specimen after the experiment.

![Macroscopic Crack](image)

*Figure 6.9 – Load-displacement response of a two-layer woven fabric specimen with SMA wires (W2S04M-04) tested with multiple impact test with images taken at the maximum displacement of each cycle of the tests.*
6.5 Comparison of the results of impact testing for two-layer woven fabric composites with and without copper or SMA wires

Comparing the two-layer woven fabric specimens with and without copper or SMA wires, the effect of the SMA wires is extremely obvious. Figure 6.10 shows this comparison between specimen W2N04S-02, without wires, specimen W2C04S-03, with copper wires, and specimen W2S04S-03, with SMA wires, all tested with single impact tests.

![Load-displacement response of two-layer woven fabric specimens without wires (W2N04S-02), with copper wires (W2C04S-03) and with SMA wires (W2S04S-03) tested with single impact tests.](image)

All three specimens had the same stiffness with the load increasing with the same rate at the low values of displacement up to initiation of cracks just below 8mm. Specimen W2N04S-02 reached its peak load and sudden drop of load at an earlier displacement than the other specimens, at around 7.5mm. The peak load was a bit lower than of specimen W2C04S-03 and significantly lower than of specimen W2S04S-03. Specimen W2S04S-03 on the other hand continued to increase up to its peak load in a higher displacement than specimen W2C04S-03, at around 8.5mm. The sudden drop of load was very similar for the three specimens, around 0.35-04kN. After that the sudden drop of load, the effect of the wires can be identified on specimen W2S04S-03 where the load was kept at much higher values than the other two specimens for few
millimetres, which was not detected before on any other type of specimen. The energy increase from specimens without wires to specimens with SMA wires was about 2J, and from specimens with copper wires to specimens with SMA wires was about 1.5J. Specimens W2N04S-02 and W2C04S-03 were fully penetrated at around 16mm while specimen W2S04S-03 was fully penetrated after 17mm.

### 6.6 Partial penetration impact test results of two-layer woven fabric composites with and without copper or SMA wires

Two-layer woven fabric specimens with and without copper or SMA wires were tested using partial penetration impact test. In these experiments, which have been described in Chapter 3, the impactor is driven into the specimen at a constant velocity to a certain displacement and then withdrawn. The displacement used were in the range of 2mm-18mm. Figure 6.11 shows the load-displacement responses for seven specimens without wires each one impacted at different displacements. The two types of load-displacement curves that were seen in the literature [Atas and Sayman, 2008] can be seen in these results as well. Figures 6.11(a) to 6.11(f) show a closed type curve (impactor does not penetrate the specimen) and Figure 6.11(g) shows an open type curve (impactor penetrates the specimen).

The partial penetration impact experiments gave very similar results to the multiple impact experiments described earlier. Figure 6.12 shows a superimposition of the load-displacement graphs of specimens impacted in partial penetration test and the equivalent cycle from specimen W2N04M-05 which was impacted in a multiple impact test. The first two plots (Figures 6.12(a) and 6.12(b)) are almost identical due to the very small amount of damage sustained by the specimens up to 5mm in displacement. The curves for the multiple impact and partial penetration results are very similar for the higher displacements.
Chapter 6 Impact results of two-layer woven fabric specimens with and without copper or SMA wires

Figure 6.11 – Load-displacement responses of two-layer woven fabric specimens without wires tested with partial penetration impact tests at different displacements, (a) 2mm (N-02), (b) 5mm (N-05), (c) 9mm (N-09), (d) 10mm (N-10), (e) 12mm (N-12), (f) 15mm (N-15) and (g) 18mm (N-18).
Figure 6.12 – Load-displacement responses of two-layer woven fabric specimens without wires, tested with partial penetration impact tests and the equivalent cycle of specimen W2N04M-05, a) 2mm (N-02), (b) 5mm (N-05), (c) 9mm (N-09), (d) 10mm (N-10), (e) 12mm (N-12), (f) 15mm (N-15).

Figures 6.13 and 6.14 show similar comparisons of load-displacement plots, for specimens with copper or SMA wires, respectively. Again the partial penetration and multiple impact results are very similar.
Figure 6.13 – Load-displacement responses of two-layer woven fabric specimens with copper wires, tested with partial penetration impact tests and the equivalent cycle of specimen W2C04M-01, a) 10mm (C-10), (b) 12mm (C-12).

Figure 6.14 – Load-displacement responses of two-layer woven fabric specimens with SMA wires, tested with partial penetration impact tests and the equivalent cycle of specimen W2S04M-07, a) 10mm (S-10), (b) 12mm SN-12.

6.7 Comparison of the results of impact testing for eight-, four- and two-layer woven fabric composites with and without wires

Figure 6.15 shows the load displacement response of the nine specimens impacted with single impact test. The specimens are eight-layer of woven fabric without wires (W8N04S-01), with copper wires (W8C04S-06H) and with SMA wires (W8S04S-03), four-layers of woven fabric without wires (W4N04S-02), with copper wires (W4C04S-03) and with SMA wires (W4S04S-02); and two-layer of woven fabric without wires (W2N04S-03), with copper wires (W2C04S-03) and with SMA wires (W2S04S-02). The increase of load during impact of the four- and two-layer woven
fabric specimens is non-linear whereas for the eight-layer woven fabric specimens, is linear. The peak load and the sudden drop of load occur at around the same displacement for all specimens. Table 6.4 shows the average values of the peak load, the penetration energy and the average thickness for the eight-, four- and two-layer woven fabric specimens with and without copper or SMA wires tested with single and multiple impact tests.

![Diagram](image)

Figure 6.15 – Load-displacement response of nine specimens impacted with single impact test, with eight-layer of woven fabric without wires (W8N04S-01), with copper wires (W8C04S-06H) and with SMA wires (W8S04S-03), with four-layer of woven fabric without wires (W4N04S-02), copper wires (W4C04S-03) and SMA wires (W4S04S-02) and with two-layer of woven fabric without wires (W2N04S-02), copper wires (W2C04S-03) and SMA wires (W2S04S-03).

Evaluating the differences that the wires made when they were inserted in the specimens the following conclusions can be pointed out. The increase of peak load from two-layer woven fabric specimen without wires to the one with copper wires was 7.6% whereas for the four-layer woven fabric specimens was 20% decrease and for eight-layer woven fabric specimens was 23%. The increase of energy for the two-layer woven fabric specimens without wires to specimens with copper wires was 16% twice than the increase of the four-layer specimens (7.1%) and close to the increase for eight-layer specimens (20%). When comparing the increase on the values when SMA wires were introduced the values of the eight-layer woven fabric specimens were lower than the ones when copper wires were inserted, 16% for peak load and
12% for energy. There was a decrease of 6.3% of peak load and an increase of 7.1% of penetration energy was observed from four-layer woven fabric specimens without wires to four-layer woven fabric specimens with SMA wires. A significant 33% increase of penetration energy was observed from two-layer woven fabric specimens without wires compared to two-layer woven fabric specimens with SMA wires. The increase of peak load is 11%. Looking at these values, it can be seen that the two-layer woven fabric specimens with SMA wires showed the higher improvement on energy.

<table>
<thead>
<tr>
<th>Type of Specimen</th>
<th>Peak load (kN)</th>
<th>Penetration Energy (J)</th>
<th>Average thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight-layer woven fabric specimens without wires</td>
<td>3.7±0.5</td>
<td>34±3</td>
<td>2.7±0.1</td>
</tr>
<tr>
<td>Eight-layer woven fabric specimens with copper wires</td>
<td>4.6±0.1</td>
<td>40.7±0.6</td>
<td>2.81±0.05</td>
</tr>
<tr>
<td>Eight-layer woven fabric specimens with SMA wires</td>
<td>4.35±0.09</td>
<td>38.0±0.8</td>
<td>2.93±0.04</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens without wires</td>
<td>2.4±0.7</td>
<td>14±1</td>
<td>1.43±0.05</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens with copper wires</td>
<td>1.9±0.1</td>
<td>15.0±0.6</td>
<td>1.71±0.04</td>
</tr>
<tr>
<td>Four-layer woven fabric specimens with SMA wires</td>
<td>2.2±0.1</td>
<td>15.3±0.6</td>
<td>1.60±0.02</td>
</tr>
<tr>
<td>Two-layer woven fabric specimens without wires</td>
<td>1.05±0.07</td>
<td>5.5±0.4</td>
<td>0.79±0.02</td>
</tr>
<tr>
<td>Two-layer woven fabric specimens with copper wires</td>
<td>1.13±0.02</td>
<td>6.4±0.3</td>
<td>1.0±0.3</td>
</tr>
<tr>
<td>Two-layer woven fabric specimens with SMA wires</td>
<td>1.17±0.08</td>
<td>7.3±0.3</td>
<td>1.04±0.05</td>
</tr>
</tbody>
</table>

Table 6.4 – Average values of the peak load, the penetration energy and the average thickness for the eight-, four- and two-layer woven fabric specimens with and without copper or SMA wires tested with single and multiple impact tests.

A number of empirical relationships can be found for the behaviour of the penetration energy and peak load with the thickness of the specimens, although the origin of these relationships is not clear. Figure 6.16 shows a plot of average penetration energy against the thickness of specimens with and without copper or SMA wires. The penetration energy increases with the thickness, although the relationship is clearly non-linear. The relationship shows a reasonable agreement with Equation 2.4 (which suggests that penetration energy is proportional to thickness to the power of 1.4). The solid line in Figure 6.16 represents energy depending of $t^{1.4}$. This is discussed further in the following chapter. The penetration energy is higher for the components with additional SMA wire reinforcement in the case of two-layer composites suggesting that higher volume fractions of SMA wire are better.
Similarly, the peak load and the thickness of woven fabric layers for specimens with and without copper wires were plotted (Figure 6.17) and it was notice that peak load is proportional to thickness to the power of 1.5, suggested in the literature (Chapter 2 – Equation 2.2). The solid line in Figure 6.17 represents load depending of $t^{1.5}$. Finally, a plot of average penetration energy of eight-, four-, and two-layer woven fabric specimens with and without copper or SMA wires is shown plotted against the average peak load in Figure 6.18, showing a linear relationship.

![Figure 6.16 - Penetration energy-thickness response for eight-, four- and two-layer woven fabric specimens with and without copper or SMA wires.](image)

![Figure 6.17 - Peak load-thickness response for eight-, four- and two-layer woven fabric specimens with and without copper or SMA wires.](image)
Figure 6.18 – Penetration energy–peak load for eight-, four- and two-layer woven fabric specimens with and without copper or SMA wires.

6.8 Summary

Throughout Chapters 5 and 6, specimens with different number of woven fabric layers, with and without reinforced copper or SMA wires, were impacted and the load-displacement data were analysed. It was seen that for low volume fractions of SMA wires, the difference between specimens with and without wires was small, whereas when the volume fraction of SMA wires increased the effect of the wires was more obvious and the increase of energy absorbed was higher. The effect of the SMA wires was more obvious after the peak load was reached and the sudden drop of load occurred which indicates the initiation of penetration. For the eight-layer specimens, the load-displacement curves were linear whereas for the four- and two-layers, the non-linearity is probably due to membrane stretching. The next chapter presents energy analysis of the composites during impact.
Chapter 7

Energy analysis

7.1 Introduction

In this chapter the energies which can be derived from the impact tests are analysed according to a method suggested by Martello and colleagues (2006), discussed earlier in the literature review (Chapter 2). The energies from eight-, four- and two-layer woven fabric specimens tested with multiple or partial penetration impact tests were analysed using this method. Also, the absorbed and impact energies from partial penetration impact tests were investigated to identify any differences between two-layer woven fabric specimens, with and without copper or SMA wires. An attempt was made to predict the penetration energy using a relationship from the literature. Also, an attempt was made to calculate the energy needed to fail the wires in the impact area of a composite.

7.2 Energy analysis

Martello et al (2006) suggested an empirical method for correlating absorbed and impact energies in drop-weight tests, having carried out tests on a wide range of composites laminates. They used drop weight impact apparatus to test woven carbon fabric laminates with epoxy resin matrices and four different stacking sequences. They perform partial penetration and full penetration on the laminates, with different impact energy values and impact velocities. In this approach, the energy absorption of a composite panel during a particular test ($U_{abs}$), the impact energy for that test ($U_{imp}$),
were normalised by the penetration energy of the specimen ($U_p$). Penetration energy was chosen to be the most suitable normalised parameter because not only does it represent the limiting impact condition but it also represents the maximum energy absorption of a laminate. They named $\frac{U_{imp}}{U_p}$ as the “impact intensity coefficient” and $\frac{U_{abs}}{U_p}$ as the “absorption coefficient”. By plotting the impact intensity coefficient against the absorption coefficient for different laminates with different thicknesses and architecture, they noticed that all energy absorptions follow a single curve. From this study, they were able to suggest that a remarkably simple empirical relationship connects these energies; i.e.

$$\frac{U_{abs}}{U_p} = \left(\frac{U_{imp}}{U_p}\right)^2$$  \hspace{1cm} (2.5)

Obviously, for very low impact energies, where no damage occurs and $U_{abs}$ is almost zero, this expression cannot be valid. The experimental results described in Chapters 5 and 6 can provide measurements of the three quantities, $U_{abs}$, $U_{imp}$, and $U_p$. Hence, it is possible to investigate whether this expression holds for the composites tested in this work which have been tested using a different experimental technique from Martello et al (2006). The impact intensity and absorption coefficients have been found for the different type of woven fabric composites, with and without reinforcing copper or SMA wires, impacted using multiple impact and single impact tests. Additional data from the partial penetration impact tests were also analysed.

### 7.3 Energy analysis of the current experimental technique

The energies involved in the analysis of the experimental technique used in the work the penetration energy, the impact energy and the energy absorption. Figure 7.1 shows a schematic of a load-displacement plot for an impactor displacement of 10mm using the servo-hydraulic test machine, explaining these energies. The impact energy ($U_{imp}$) is the work done during the impactor being forced to a particular displacement in the impact test (in this example 10mm) and is found by the area under the load-
displacement plot up to that point. The energy absorbed by the specimen ($U_{\text{abs}}$) is energy not recovered, during unloading from the measurement displacement (10mm) and this is calculated by the difference between the energy recovered during unloading (from the impactor displacement of 10mm) and the impact energy. The penetration energy ($U_p$) of the specimen is defined as the energy needed to completely penetrate the specimen and it is the sum of the three shaded areas shown in the figure. For partial penetration impact test $U_p$ is obtained from a separate experiment where the specimen is penetrated completely in an impact test. The data from the multiple impact tests described in Chapters 5 and 6, were also used for the energy analysis. The impact and absorbed energies of each specimen were calculated for each cycle of impact, considering the energies of the previous impact cycle and the overlapping of the cycles, as explained in Chapter 3. The penetration energy was taken to be the overall energy needed to penetrate the specimens.

![Figure 7.1 - A schematic of load-displacement graph for an impact test and the distribution of energies.](image)

**7.4 Results of the energy analysis**

**7.4.1 Multiple impact experiments**

Figure 7.2 shows the absorption coefficient-impact intensity coefficient plot for eight-, four-, and two-layer woven fabric specimens without wires tested using multiple impact experiments. Equation 2.5 has been added for comparison. It can be seen that, in general, the data show good agreement with Equation 2.5 for these materials for the
lower values i.e. $\frac{U_{imp}}{U_p} = 0.4$ and at the higher values above $\frac{U_{imp}}{U_p} = 0.8$. In the region 0.45-0.8 the agreement is poorer. In the impact experiments, this region corresponds to displacements of 8mm-10mm which is just after the major load drop in the load-displacement curve.

Looking at the absorption coefficient-impact intensity coefficient plot for eight-, four- and two-layer woven fabric specimens with reinforcing copper wires, a very similar behaviour is seen (Figure 7.3). Again, the values of absorption coefficient are a little higher than suggested by Equation 2.5 in the region of $\frac{U_{imp}}{U_p} = 0.4$-0.8, which corresponds to the region just after the major load drop.

The result for the specimens reinforced with SMA wires is shown in Figure 7.4. In this case, the data from the eight-, four- and two-layer woven fabric specimens with reinforcing SMA wires fit Equation 2.5 quite well for all values of impact intensity coefficient although data from the eight-layer woven fabric with reinforced SMA wires lie above the line for the region of $\frac{U_{imp}}{U_p} = 0.4$-0.8 of the impact intensity coefficient.
To investigate whether a better fit may be possible with a different power exponent in Equation 2.5, log-log plots of absorption and impact intensity coefficients were
plotted. Figure 7.5 shows these plots, and suggest that a power of 1.5 may be better, especially for the specimens with and without copper wires. Figure 7.6 show the earlier figures re-plotted for power exponents of 1.5 and 2. Most of the points for all specimens lie between the two powers suggesting a relationship

\[ \frac{U_{\text{abs}}}{U_p} = \left( \frac{U_{\text{imp}}}{U_p} \right)^\alpha \]

where $\alpha$ lies between 1.5 and 2.

Figure 7.5 – Log-log plots of Absorption coefficient-Impact Intensity coefficient response for eight-, four-, and two-layer woven fabric specimens (a) without wires, (b) with copper wires and (c) with SMA wires.
7.4.2 Partial penetration experiments

In section 6.6 (Chapter 6) the results of partial penetration impact experiments were described where impactor is driven into the specimen to a certain displacement. The impact and absorbed energies ($U_{imp}$ and $U_{abs}$) of the partial penetration impact experiments were measured from the graphs and the penetration energy ($U_p$) was taken as the energy needed to fully penetrate the specimen (18mm). Figure 7.7 shows the results from the energy analysis of these experiments plotted according to Equation 2.5. The data show a good agreement with Equation 2.5 although, again, the region between $0.4 < \frac{U_{imp}}{U_p} < 0.8$ has a slightly higher value of absorption coefficient than Equation 2.5 would suggest. Figures 7.8 and Figure 7.9 also show the absorption coefficient-impact intensity coefficient response for two-layer woven fabric specimens with reinforcing copper wires and for two-layer woven fabric specimens with reinforcing SMA wires respectively, both types impacted with partial penetration impact test. These results confirm the multiple impact results shown earlier,
suggesting that the specimens with reinforcing SMA wires are a closer fit to Equation 2.5 than the specimens without wires or with reinforcing copper wires, especially in the region \(0.4 < \frac{U_{imp}}{U_p} < 0.8\), thought it is not clear why this should be the case.

Figure 7.7 – Absorption coefficient-Impact Intensity coefficient response for two-layer woven fabric specimens without wires, impacted with partial penetration impact experiments.

Figure 7.8 – Absorption coefficient-Impact Intensity coefficient response for two-layer woven fabric specimens with reinforcing copper wires, impacted with partial penetration impact experiments.
Although the use of the empirical Equation 2.5 is interesting, it does not bring out the differences between the specimens with respect to energy absorption. To compare energy absorption \( U_{ab} \) between the different types of specimens, the energy absorption was plotted against the maximum displacement of the impactor and impact energy.

Figure 7.10 shows the plot for two-layer woven fabric specimens, with and without copper or SMA wires, for the partial penetration impact experiments with respect to the maximum displacement. At low displacement values, the energy absorption was about the same for all types of specimens and there very little difference between all the specimen types up to 10mm which is the beginning of the through-thickness penetration of the specimens. However, for displacement above 12mm, specimens with reinforcing SMA wires showed higher energy absorption than the other specimens. Specimens with copper wires showed more or less the same results as specimens without wires. Summarising the energy absorption results, it is clear that it is only for the higher impact displacements that the energy absorption for the specimens with SMA wires is the greatest. Figure 7.11 shows the energy absorption,
U_{abs}, plotted against the impact energy, U_{imp}. The results in Figure 7.10 show that the SMA wires could be expected to be more useful for impact events where there is sufficient energy for the impactor to penetrate the specimen. For lower impact energies, there would be no advantage in using SMA wires.

**Figure 7.10** – Energy absorption-displacement response for two-layer woven fabric specimens with and without copper or SMA wires, impacted with partial penetration impact experiments.

**Figure 7.11** – Energy absorption-impact energy response for two-layer woven fabric specimens with and without copper or SMA wires, impacted with partial penetration impact experiments.
Caprino and Lopresto (2001) suggested an empirical relationship to predict energy of penetration ($U_p$) from the laminate thickness ($t$), volume fraction ($V_f$) and the diameter of the impactor ($d$):

$$U_p = 0.49(tV_f d)^{1.4}$$  \hspace{1cm} (2.4)

Equation 2.4 was used to predict the penetration energy of eight-, four- and two-layer woven fabric composites without wires. Table 7.1 shows the average predicted and the average experimental values of penetration energy for these specimens. Four specimens of each type of composites were used to find the average values. Figure 7.12 shows the predicted penetration energy plotted against the measured penetration energy for of all specimens used; a reference line has been showing where the predicted and experimental values would be equal. It can be seen that the average predicted values of penetration energy are in good agreement with the experimental values.

<table>
<thead>
<tr>
<th>Type of composite</th>
<th>Predicted $U_p$</th>
<th>Experimental $U_p$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight-layer woven fabric without wires</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Four-layer woven fabric without wires</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Two-layer woven fabric without wires</td>
<td>4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

*Table 7.1 – Average values of predicted and experimental penetration energy of eight-, four- and two-layer woven fabric specimens without copper or SMA wires.*

As was seen in the previous chapters (Chapter 5-6), specimens with copper and SMA wires require more energy for full penetration. Table 7.2 shows the average penetration energy of two-layer woven fabric specimens with and without copper or SMA wires. To investigate whether this extra energy is due to the deformation and failure of the wires in the specimen, an attempt has been made to calculate the energy needed to fail the wires in the impact area. Figure 7.13 shows a schematic of a specimen and the impact area. The impactor has a diameter of 16mm. The intensive damage around the impactor is generally a circular area of approximate 20mm diameter. Around this intensive area is another region which apparently consist of stress whitening (though, in fact, this is matrix cracking and delamination; see Chapters 8 and 9).
Figure 7.12 – Predicted penetration energy-experimental penetration energy response for eight-, four and two-layer woven fabric specimens without copper or SMA wires.

Several assumptions have been made in these calculations. First it has been assumed that all the wires fail in the intensive damage region which was taken to be a square with dimensions 20mm × 20mm. This is not exactly true because not all the wires in this region break, as will be show in the macroscopic analysis (Chapter 8) and the impact area is circular with 20mm diameter. However, knowing the area of the impact area and the spacing of the wires in the specimen (1.5mm) and the number of wires in the impact area (27 wires), the total volume of the wires can be found. Using the energy per unit volume to fracture the copper or SMA wires (see Chapter 4) it was found that 0.4J and 1.6J were needed to fracture the copper and SMA wires in the impact area, respectively. Comparing these values with the values of enhanced energy in Table 7.2, it can be seen that not all the extra energy is solely due to deformation and failure of the wires. Presumably friction between the wires and the matrix makes an additional contribution, together with debonding of the wires from the matrix.

<table>
<thead>
<tr>
<th>Type of composite</th>
<th>Energy (J)</th>
<th>Increase of energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-layer woven fabric without wires</td>
<td>5.5</td>
<td>-</td>
</tr>
<tr>
<td>Two-layer woven fabric with copper wires</td>
<td>6.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Two-layer woven fabric with SMA wires</td>
<td>7.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 7.2 – Energy of penetration of two layer woven fabric specimens with and without copper or SMA wires, and increase of energy from specimens without wires to specimens with wires.
7.6 Summary

The data from the multiple impact tests and from the partial penetration impact tests showed a good agreement with an empirical relationship for relating energies involved in an impact test that Martello and colleagues (2006) suggested (Equation 2.5). Eight-, four- and two-layer woven fabric specimens, with and without reinforcing copper wires or SMA wires showed, a slightly higher values of the absorption coefficient for the region $0.4 < \frac{U_{\text{imp}}}{U_p} < 0.8$ than the Equation 2.5 suggested, but the four- and two-layer woven fabric specimens with SMA wires showed a good agreement, even in that region. For all the materials tested an empirical expression of the form

$$\frac{U_{\text{abs}}}{U_p} = \left( \frac{U_{\text{imp}}}{U_p} \right)^{\alpha}$$

is appropriate, where $\alpha$ lies between 1.5 and 2.

Comparing the energy absorption of different types of specimens at the same maximum displacement showed that before the first significant macroscopic crack, the specimens have similar energy absorption. After the first through-thickness crack the specimens with reinforcing SMA wires showed higher energy absorption than the rest of the specimens. This suggests that the SMA wires tend to be useful for absorption energies high enough to penetrate the specimen. This result confirmed when absorption energies are plotted against impact energies for all type of...
specimens. The beneficial effect of the SMA wires for the high impact/penetration results has been discussed in terms of the high energy absorption to failure of the SMA wires. The predicted values of penetration energy found by using Equation 2.4 for eight-, four and two-layers woven fabric composites without wires agree with the experimental values of penetration energy for those composites found by performing impact tests.

By performing a series of simple calculations and assuming that all wires fail in the impact area, the energy needed to break the copper and SMA wires was found to be less than the increase in energy from composites with copper or SMA wires and composites without wires and therefore not all the extra energy is solely due to deformation of the wires but presumably friction of the wires and the matrix makes an additional contribution.

The next chapter (Chapter 8) shows the result of the macroscopic analysis of two-layer woven fabric specimens with and without reinforcing copper or SMA wires, impacted with partial penetration impact tests.
Chapter 8

Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires

8.1 Introduction

The damage developed in two-layer woven fabric specimens with and without reinforcing copper or SMA wires, impacted with partial penetration impact tests has been investigated. Development of damage has been identified for different impact displacements, and in this chapter, the macroscopic observations are described for the different specimen types (the following chapter describes the microscopic observations).

8.2 Composites without reinforcing wires

Two-layer woven fabric specimens without any reinforcing wires have been partially impacted with displacements in the range of 2mm-18mm. In these experiments, the impactor moves a set distance into the specimen and then withdraws (partial impact). Figure 8.1 shows images of specimen N-02, which was impacted to 2 mm. Figure 8.1(a) shows the specimen at low magnification and the damage area investigated under the microscope is indicated. Figures 8.1(b) and 8.1(c) show the damage area at higher magnification. The views of the composites is said to be of the 'exit layer' i.e. the face the impactor would exit the specimen (Figure 8.1(b)), or the 'impact layer' i.e. the face the impactor would enter the specimen (Figure 8.1(c)).
For the 2mm partial penetration, the macroscopic images suggest damage in the specimen is in the exit layer only, in the form of stress-whitening which is delineating the position of the fibre tows in the exit layer. The stress-whitening seen in Figure 8.1(c) is actually in the ply near exit layer. No cracks were obvious in any layer of the specimen at this magnification. However, as will be seen in Chapter 9, sectioning the specimens revealed that matrix cracks and delaminations had formed even at this low impact displacement.

The next specimen to be investigated was specimen N-04, which was partially impacted with a displacement of 4mm. Both layers (impact and exit) suffered damage in the form of stress-whitening which indicated the position of the fibres in the tows, but the damage in the impact layer was less than the damage in the exit layer. In addition, the exit layer had more damage than the equivalent exit layer of specimen N-
02. Of particular importance, in the exit layer the first visible matrix cracks could easily be seen and these cracks were not visible within the impact layer. Figure 8.2 shows several images of the damage in the exit layer and Figure 8.2(a) shows the damage area from the exit layer (indicated by a circle) at low magnification. Figure 8.2(b) shows the matrix crack formation in the exit layer (which appear as jagged white lines) and Figure 8.2(c) was taken by placing the specimen at an angle so that the matrix cracks were shown more clearly. The two last images, Figures 8.2(d) and 8.2(e), show the matrix crack in the exit layer at higher magnification. Point C is placed above of one of the matrix cracks in Figure 8.2(d). The same matrix crack is indicated by point C in Figure 8.2(e) at higher magnification. These image show matrix cracks in the exit layer radiating out from the centre of the impact about 6mm. The matrix cracks appear to be oriented parallel to the impact direction.

Figure 8.2 – Images of the exit layer of a two-layer woven fabric specimen without wires (specimen N-04) impacted with partial penetration impact test up to 4mm; taken at different magnifications showing a matrix crack at C.
Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.3 shows an image of the impact layer of specimen N-04. In the impact layer only stress-whitening was found but no matrix cracks were visible for this view of the specimen at this magnification. The matrix cracks seen in Figure 8.3 are in the exit layer.

![Image of the impact layer of a two-layer woven fabric specimen without wires (specimen N-04) impacted with partial penetration impact test up to 4mm.](image)

Specimen N-07 was impacted to 7mm and after impact it showed a small permanent deformation in the impact area. The amount of damage has increased compared to specimen N-04 and a few individual fibres from the tows were broken in the exit layer. Figure 8.4 shows images of the exit surface of specimen N-07, with Figure 8.4(a) showing the damage area indicated by a circle. Figure 8.4(b) is a low magnification image of the specimen showing matrix cracks. Figure 8.4(c) shows matrix cracks at higher magnification and Figure 8.4(d) shows fracture fibres at F. Specimen N-07 viewed from the impact side shows circular matrix cracks, around the impact area (Figure 8.5). The inner crack has a radius of about 3.6mm and subsequent cracks are about 1mm apart. The matrix cracks are seen clearly at low magnification (Figure 8.5(a)), and higher magnification (Figure 8.5(b)).

The next specimen, specimen N-09, was impacted with a 9mm displacement, which with respect to the load-displacement plot, is just after the sudden drop of load that the specimen experiences which is believed to be due to the first macroscopic, through-thickness crack. This was confirmed by the small, but visible penetration of the specimen shown at P (Figure 8.6). The specimen suffered higher damage than the
previous specimens with more cracks and fibre fractures than before in both layers. Interestingly, few tows were found fractured in both layers.

**Figure 8.4** – Images of the exit layer of a two-layer woven fabric specimen without wires (specimen N-07) impacted with partial penetration impact test up to 7mm; taken at different magnifications, showing a fibre fracture at F.

**Figure 8.5** – Images of the impact layer of a two-layer woven fabric specimen without wires (specimen N-07) impacted with partial penetration impact test up to 7mm; taken at different magnifications.
Chapter 8

Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.6(a) shows the damage area from the exit layer at low magnification. Figures 8.6(b) and 8.6(c) show damage in the exit layer, focusing on the small penetration of the specimen which is seen as a dark area at P. These images also show extensive matrix cracking and fibre fractures.

![Image](a)

![Image](b)

![Image](c)

Figure 8.6 – Images of the exit layer of a two-layer woven fabric specimen without wires (specimen N-09) impacted with partial penetration impact test up to 9mm; taken at different magnifications, showing initiation of penetration at P.

Figure 8.7 shows images from the impact layer of specimen N-09. The penetration of the specimen is again visible as a dark area. Circular matrix cracks can be seen in Figure 8.7(a) and Figure 8.7(b) shows a tow fracture close to the point of penetration indicated by the point F. The inner circular matrix crack has a radius of about 4mm and subsequent cracks are about 1mm apart. Circular cracks on impacted woven fabric composites were found from other researches as well [e.g. Sutherland and Soares, 1999].

Not surprisingly, the specimen impacted with 12mm displacement suffered greater damage than the other specimens. The penetration of the specimen was more obvious,
with broken tows in the shape of a cross in the middle of the impact area. Kim and Sham (2000) notice the damage in their woven fabric laminates had a shape of a cross lying in the warp and weft directions, as well. Figure 8.8(a) shows the general area of damage for specimen N-12 (exit layer). Figure 8.8(b) shows the penetration of the specimen; part of the cross and the failure of the tows is clearly shown.

![Figure 8.7](image_url)  
(a) (b)

**Figure 8.7** – Images of the impact layer of a two-layer woven fabric specimen without wires (specimen N-09) impacted with partial penetration impact test up to 9mm; taken at different magnifications, showing circular matrix cracks, penetration at P and a tow fracture at F.

![Figure 8.8](image_url)  
(a) (b)

**Figure 8.8** – Images of the exit surface of a two-layer woven fabric specimen without wires (specimen N-12) impacted with partial penetration impact test up to 12mm; taken at different magnifications.

Figure 8.9 shows an image of the impact layer of specimen N-12. The permanent deformation of the specimen has made the upper part of the image out of focus. The
fractured tows are also obvious here and circular matrix cracks can be seen with a spacing of about 1mm.

Figure 8.9 – Image of the impact layer of a two-layer woven fabric specimen without wires (specimen N-12) impacted with partial penetration impact test up to 12mm.

Specimen N-15, which was partially penetrated with a displacement of 15mm, suffered heavy damage with almost all the tows in the impact area fractured. Matrix cracks extended throughout the impact area in both layers and one tow in the impact layer was separated from the specimen. Figure 8.10 shows images of the two layers of specimen N-15.

Figure 8.10 – Images of a two-layer woven fabric specimen without wires (specimen N-15) impacted with partial penetration impact test up to 15mm; showing (a) the indicated damage area from the exit layer and at higher magnification (b) the exit layer and (c) the impact layer.

Specimen N-18 was fully penetrated at 18mm causing even more damage than that of the previous specimens. Figure 8.11 shows images of the two layers of specimen N-
18. Figure 8.11(a) indicates the damage area from the exit layer and Figures 8.11(a) and 8.11(b) show the penetration of the specimen in the exit layer (Figure 8.11(a)) and the impact, respectively, layer showing evidence of the disbonding of a tow from the specimen indicated by the point T.

![Image](image_url)

Figure 8.11 – Images of a two-layer woven fabric specimen without wires (specimen N-18) impacted with partial penetration impact test up to 18mm; showing (a) the indicated damage area from the exit layer, and at higher magnifications (b) the exit layer and (c) the impact layer showing the disbanding of a tow at T.

Table 8.1 shows the approximate damage area, estimated to be the whitening area, of the exit layer of the two-layer woven fabric specimens without wires. This damage area was plotted against the maximum displacement of the impactor into the specimens (Figure 8.12). As expected, the damage area increases as the displacement of the impactor into the specimen increases; the damage area reached a maximum damage area of about 575mm$^2$ at 18mm where the specimen is completely penetrated by the impactor. The damage area does not, of course, represent accurately the damage of the specimens because it does not take account properly for area of all the
delaminations, between the different plies. For example, specimens N-04 and N-07 have the same estimated value of damage area by this measure, but the damage in specimen N-07 is greater than the damage within specimen N-04 because of multiple delaminations and other intense damage (matrix cracks, tow fractures) within the “damage area”.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement (mm)</th>
<th>Damage area (mm²)</th>
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</thead>
<tbody>
<tr>
<td>N-02</td>
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<tr>
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<td>415</td>
</tr>
<tr>
<td>N-18</td>
<td>18</td>
<td>575</td>
</tr>
</tbody>
</table>

Table 8.1 – Estimated damage area of two-layer woven fabric specimens without wires impacted with partial penetration impact tests.

Figure 8.12 – Damage area-displacement response of two-layer woven fabric specimens without wires impacted with partial penetration impact tests.

During the macroscopic analysis the number of fractured tows found on the specimens was counted as a function of the displacement. Figure 8.13 shows a graph of the number of fractured tows against the displacement response for the specimens without copper or SMA wires. As mentioned above, the first tow fracture appeared at a displacement of 9mm (specimen N-09) and the number of fractured tows increased
as the displacement increased up to 15mm where all the tows in the impact area fractured.

![Graph](image)

Figure 8.13 – Number of fractured tows-displacement response of two-layer woven fabric specimens without wires, impacted with partial penetration impact tests.

### 8.3 Composites with reinforcing copper wires

Two-layer woven fabric specimens with reinforcing copper wires, which had been impacted with displacements in the range of 2mm-18mm, were investigated under the microscope. Specimen C-02, impacted with a displacement of 2mm, showed formation of stress-whitening on the exit layer only (as specimen N-02 had showed as well). In the damage area, which is indicated in Figure 8.14(a), the copper wires are clearly visible. Figure 8.14(b) shows an image of the exit layer of specimen C-02, showing the stress-whitening as the white areas and behind the stress whitening the copper wires can be seen. Figure 8.14(c) is an image of the impact layer of the same specimen. In this image, there is no visible damage in the impact layer (as in specimen N-02). No cracks were visible anywhere in the specimen with the macroscopic analysis although the microscopic analysis in Chapter 9 shows that matrix cracks and delaminations had, in fact, formed.

For specimen C-05, which was impacted to a displacement of 5mm, matrix cracks were seen in the exit layer only, whereas in the impact layer only stress whitening was seen. This is similar to the macroscopic observations on specimen N-04 (impacted up to 4mm). The copper wires seem to be unaffected by the impact. Figure 8.15 shows images of overall the damage area (Figure 8.15(a)), the exit layer (Figure 8.15(b) and 8.15(c)) and the damage of the impact layer (Figure 8.15(d) and 8.15(e)).
Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.14 – Images of a two-layer woven fabric specimen with copper wires (specimen C-02) impacted with a partial penetration impact test up to 2mm; showing (a) the indicated damage area from the exit layer and at higher magnification (b) the exit layer and (c) the impact layer.

Figure 8.15 – Images of a two-layer woven fabric specimen with copper wires (specimen C-05) impacted with partial penetration impact test up to 5mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer and (d) and (e) the impact layer, at different magnifications.
Specimen C-08 (Figure 8.16(a)-8.16(d)) was impacted at 8mm, which is a displacement just after the sudden drop of load in the load-displacement curve and the specimen was permanently deformed. The drop in load appears to have caused by tow fracture near the centre of the impact forming a horizontal line which can be seen in Figure 8.16(b) at the point marked T (exit layer). The copper wires were permanently deformed as well but no evidence of broken wires was found. Figure 8.17 shows images from the impact layer of the same specimen (specimen C-08). Figure 8.17(a) shows the impact layer at low magnification, and again, circular matrix cracks can be seen around the impact area. The radius of the inner circle is 3.6mm and the cracks are about 1mm apart. Figure 8.17(b) shows a tow fracture.

Figure 8.16 – Images of the exit layer of a two-layer woven fabric specimen with copper wires (specimen C-08) impacted with partial penetration impact test up to 8mm; taken at different magnifications, showing tow fractures at T.
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Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.17 - Images of the impact layer of a two-layer woven fabric specimen with copper wires (specimen C-08) impacted with partial penetration impact test up to 8mm; at different magnifications.

For specimen C-10, which was impacted with a displacement of 10mm, the first evidence of fractured copper wire was found. The specimen remained permanently deformed more than specimen C-08 and a small penetration was created in the middle of the impact area. The number of matrix cracks and stress-whitening was increased dramatically. Figure 8.18(a) to 8.18(c) shows images of the exit layer of specimen C-10. Figure 8.18(b) shows fractured tows as a consequence of penetration of the specimen, at P, and a number of matrix cracks. Figure 8.18(c) shows tow fractures and a fractured copper wire, at W.

Figure 8.18 - Images of the exit layer of a two-layer woven fabric specimen with copper wires (specimen C-10) impacted with partial penetration impact test up to 10mm; taken at different magnifications, showing a macroscopic crack at P and a broken wire at W.
Figure 8.19 shows the impact layer of the same specimen (specimen C-10) with a through-thickness crack and circular matrix cracks (Figure 8.19(a)) and a fractured copper wire (Figure 8.19(b)). The radius of the inner circle of the circular matrix cracks was about 3.8mm and the cracks were about 1mm apart for specimen C-10 as for specimen C-08.

Figure 8.19 – Images of the impact layer of a two-layer woven fabric specimen with copper wires (specimen C-10) impacted with partial penetration impact test up to 10mm; at different magnifications showing a macroscopic crack at P and a broken wire at W.

Specimen C-12 was impacted to a displacement of 12mm and a larger penetration area was evident in the middle of the impact area. Figures 8.20(a)-8.20(e) show images of the exit and impact layer of specimen C-12. Figure 8.20(b) shows the gap formed in the composite as a result of the penetration and Figure 8.20(c) shows broken copper wires at W and fibre fractures in the exit layer. Figure 8.20(d) shows the penetration of the specimen (at P) viewed from the impact layer and Figure 8.20(e) shows tow fracture at T and broken wires at W again from the impact layer.

Similar results were found for specimen C-15 impacted to 15mm displacement. This specimen was almost fully penetrated by the impactor. More matrix cracks and fibre fractures were found in and around the impact area, in both layers, and all the copper wires in that area failed. Figures 8.21(a)-8.21(e) show images from the exit and impact layers of specimen C-15. Figure 8.21(b) shows the penetration of the specimen from the exit layer and Figure 8.21(c) shows a higher magnification image including
two broken wires. Figures 8.21(d) and 8.21(e) show the impact layer penetration and some tow fractures.

Figure 8.20 – Images of a two-layer woven fabric specimen with copper wires (specimen C-12) impacted with partial penetration impact test up to 12mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer and (d) and (e) the impact layer, at different magnifications showing broken wires at W, penetration at P and tow fracture at T.

Finally, specimen C-18, with an 18mm displacement, was investigated (Figures 8.22(a)-8.22(c)). The specimen was fully penetrated by the impactor and the Figures 8.22(b) and 8.22(c) show the exit and impact layer of specimen C-18, respectively, with fractured copper wires visible in both images.
Figure 8.21 – Images of a two-layer woven fabric specimen with copper wires (specimen C-15) impacted with partial penetration impact test up to 15mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer and (d) and (e) the impact layer, at different magnifications.

Table 8.2 shows the approximate damage area of the exit layer of the two-layer woven fabric specimens with copper wires, with the damage area defined as before. The damage area was plotted against the maximum displacement of the impactor into the specimens (Figure 8.23). The damage area increases as the displacement of the impactor into the specimen increases, until the displacement of 12mm where the damage area reached its maximum value of about 530mm². Even though specimens C-12, C-15 and C-18 have the same value of damage area, the damage in that area is much greater for specimen C-18 than the other two specimens, and the damage of specimen C-15 is more than that in specimen C-12.
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Figure 8.22 – Images of a two-layer woven fabric specimen with copper wires (specimen C-18) impacted with partial penetration impact test up to 18mm; showing (a) the damage area from the exit layer indicated by a circle, (b) the exit layer and (c) the impact layer.

Figure 8.24 shows the number of fractured tows-displacement response for the specimens with copper wires. The first tow fracture appeared at a displacement of 8mm (specimen C-08) and the number of fractured tows increased as the displacement increased, as was seen previously with specimens without any wires, up to 15mm, where all the tows in the impact area had fractured.

<table>
<thead>
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<th>Specimen</th>
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<th>Damage area (mm²)</th>
</tr>
</thead>
<tbody>
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<tr>
<td>C-18</td>
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</tr>
</tbody>
</table>

Table 8.2 – Estimated damage area of two-layer woven fabric specimens with copper wires impacted with partial penetration impact tests.
Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.23 – Damage area-displacement response of two-layer woven fabric specimens with copper wires, impacted with partial penetration impact tests.

Figure 8.24 – Number of fractured tows-displacement response of two-layer woven fabric specimens with copper wires, impacted with partial penetration impact tests.

8.4 Composites with reinforcing SMA wires

Two-layer woven fabric specimens with reinforcing SMA wires were also investigated under the microscope to study the damage after impacts at different displacements, in the range of 2mm-18mm. Specimen S-02 was impacted to a displacement of 2mm. As with specimens N-02 (no wires) and C-02 (copper wires), no macroscopic evidence of matrix cracks were found in the specimen. Stress-whitening was evident on the exit layer and the SMA wires were unaffected by the
impact. Figures 8.25(a)-8.25(c) show images of specimen S-02 showing stress-whitening in the exit layer (Figure 8.25(b)) and the apparent absence of damage in the impact area on the impact layer (Figure 8.25(c)). However, microscopic observations on sections of the specimen (Chapter 9) showed that even for the small displacement of 2mm, matrix cracks and delaminations are formed in the specimen.

![Image of specimen S-02](image)

**Figure 8.25 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-02) impacted with partial penetration impact test up to 2mm; showing (a) the damage area from the exit layer indicated by a circle, (b) the exit layer and (c) the impact layer.**

Specimen S-05 was impacted to a displacement 5mm and it formed damage on both of its layers, with the first evidence of matrix crack on the exit layer. Only stress-whitening was found in the impact layer with no visible matrix cracks present. Here as well the SMA wires seemed to be unaffected. Figures 8.26(a)-8.26(c) show images of the exit and impact layer of specimen S-05. Figures 8.26(b) and 8.26(c) show the area of severe tow delamination and the stress-whitening area can be clearly seen. Figure 8.26(c) clearly shows the matrix cracks near the centre of impact in the exit layer. Figures 8.26(d) and 8.26(e) show the impact layer and no matrix cracks can be seen in the impact layer (note: the black dots on the image are from a marker pen on the specimen surface).
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Figure 8.26 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-05) impacted with partial penetration impact test up to 5mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer and (d) and (e) the impact layer, at different magnifications.

The next specimen, specimen S-08, was impacted to 8mm causing tow fractures in the specimen which were responsible for the slight permanent deformation of the specimen and for the sudden drop of load on the load-displacement graph. Matrix cracks were visible in both layers of the specimen. The SMA appeared to be unaffected after this impact. This was not the case for the copper wires of the corresponding impact displacement (specimen C-08). Figures 8.27(a)-8.27(c) shows images of the exit layer of specimen S-08. Figure 8.27(b) shows the impact area with some of the matrix cracks visible. Matrix cracks are more obvious in Figure 8.27(c) which also shows fibre fracture.
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Figure 8.27 – Images of the exit layer of a two-layer woven fabric specimen with SMA wires (specimen S-08) impacted with partial penetration impact test up to 8mm; taken at different magnifications.

Figure 8.28(a) and 8.28(b) show evidence of matrix cracks in the impact layer of specimen S-08. The matrix cracks are circular around the impact area of the specimen as seen in the other specimen types, but here the radius of the inner circle is 4.7mm and the cracks are 2mm apart (note: the black dots on the image are from a marker pen on the specimen surface).

Figure 8.28 – Images of the impact layer of a two-layer woven fabric specimen with SMA wires (specimen S-08), impacted with partial penetration impact test up to 8mm; taken at different magnifications.
A small penetration was found in the next specimen that was investigated, specimen S-10. This specimen was impacted to 10mm. The permanent deformation of the specimen was increased compared to specimen S-08. For specimen S-10, the SMA wires in the impact area were deformed but did not fracture. This is in contrast with specimen C-10 within which fractured copper wires was seen.

Figures 8.29(a)-8.29(e) show images of specimen S-10. Figure 8.29(b) shows the small penetration that was created on the exit layer at P and is more obvious in Figure 8.29(c) which is a magnification of the indicated area from Figure 8.29(b) also showing tow fractures at T. Figure 8.29(d) and 8.29(e) are from the impact layer of the specimen and show the circular matrix cracks (with a inner circle radius of 4mm and about 1mm between each crack) and tow fractures in the impact layer.

Figure 8.29 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-10) impacted with partial penetration impact test up to 10mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer showing penetration at P and tow fracture at T and (d) and (e) the impact layer, at different magnifications.
Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

The first evidence of fractured SMA wires was found in specimen S-12 (Figures 8.30(a)-8.30(d)) which was impacted to 12mm. Evidence of deformed and fractured SMA wire is shown in Figures 8.30(b) and 8.30(c), respectively. These images were taken from the exit layer of specimen S-12. Tow fractures can also be seen in the images. Figure 8.30(d), taken from the impact layer of the specimen, shows the circular matrix cracks and tow fracture.

![Figure 8.30](image1.png)  
(a)  
(b)  
(c)  
(d)

Figure 8.30 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-12) impacted with partial penetration impact test up to 12mm; showing (a) the damage area from the exit layer indicated by a circle, (b) and (c) the exit layer and (d) the impact layer, at different magnifications.

Specimen S-15 (Figures 8.31(a)-8.31(c)), which was impacted to 15mm, was almost penetrated completely, suffering high damage with a lot of the SMA wires failed in the impact area and other SMA wires were highly deformed. Some fibre tows were separated from the specimen on the exit layer. Figures 8.31(b) and 8.31(c) shows the
impact area of specimen S-15 from the exit and impact layers, respectively. These images show deformed and broken wires, tow fractures, matrix cracks and examples of detached tows (e.g. at T).

Figure 8.31 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-15) impacted with partial penetration impact test up to 15mm; showing (a) the damage area from the exit layer indicated by a circle, (b) the exit layer and (c) the impact layer showing the disbanding of a tow at T, at different magnifications.

Specimen S-18 (FigureS 8.32(a)-8.32(c)) was fully penetrated when impacted to 18mm displacement. Again, some of the SMA wires were highly deformed but did not fail in the impact area. Figures 8.32(b) and 8.32(c) show the impact area of specimen S-18 from its exit and impact layers, respectively. These images show deformed and broken wires and tow fractures. Matrix cracks are difficult to discern in this highly damaged region.
Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.32 – Images of a two-layer woven fabric specimen with SMA wires (specimen S-18) impacted with partial penetration impact test up to 18mm; showing (a) the damage area from the exit layer indicated by a circle, (b) the exit layer and (c) the impact layer, at different magnifications.

Table 8.3 shows the approximate damage area of the exit layer of the two-layer woven fabric specimens with SMA wires. As before, the damage area was plotted against the maximum displacement of the impactor into the specimens (Figure 8.33). The damage area increases as the displacement of the impactor into the specimen increases, until a displacement of 15mm where the damage area reached its maximum value of about 530mm². Again, the damage area does not represent accurately the damage of the specimens because more extensive damage occurs within in the form of delaminations, matrix cracks and tow fractures. Even though specimens S-15 and S-18 have the same value of damage area, the damage within specimen S-18 is greater than the damage of specimen S-15. Figure 8.34 shows the number of fractured tows-displacement response for the specimens with SMA wires. As for specimens with copper wires, the first tow fracture appeared at a displacement of 8mm (specimen S-08) and the number of fractured tows increased as the displacement increased up to 15mm, where all the tows in the impact area had fractured.
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<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement (mm)</th>
<th>Damage area (mm²)</th>
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</thead>
<tbody>
<tr>
<td>S-02</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>S-05</td>
<td>5</td>
<td>50</td>
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<td>S-08</td>
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<td>165</td>
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<td>S-10</td>
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<td>315</td>
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<tr>
<td>S-15</td>
<td>15</td>
<td>530</td>
</tr>
<tr>
<td>S-18</td>
<td>18</td>
<td>530</td>
</tr>
</tbody>
</table>

Table 8.3 – Estimated damage area of two-layer woven fabric specimens with SMA wires, impacted with partial penetration impact tests.

Figure 8.33 – Damage area-displacement response of two-layer woven fabric specimens with SMA wires, impacted with partial penetration impact tests.

Figure 8.34 – Number of fractured tows-displacement response of two-layer woven fabric specimens with SMA wires, impacted with partial penetration impact tests.
8.5 Comparison of damage development in the three materials

A brief summary of the sequence of damage development of the three different types of specimens is presented here; a full comparison is made at the end of Chapter 9. The damage of the three types of specimens showed both similarities and differences. All types of specimens had damage only in the exit layer when impacted at 2mm. Also, the formation of matrix cracks in the exit layer at 5mm impact displacement and at 8mm displacement in the impact layer was also a similarity for all three types of specimens. In addition, the first macroscopic through-thickness crack developed after 8mm for all kinds of specimens.

With regard to the specimens with wires, the copper wires retained a permanent curvature after 8mm and began to fracture from 10mm. This was not the case for the SMA wires which showed permanent deformation from 10mm and began to fracture at 12mm. After the 18mm impact displacement all the copper wires were broken in the impact area but not all the SMA wires fractured, although some of the SMA wires were heavily deformed.

Figures 8.35 and 8.36 show the damage area-displacement response, and the number of fractured tows-displacement responses, of two-layer woven fabric specimens with and without copper or SMA wires, respectively. Using these measured of damage, the estimated damage areas and the number of fractured tows of the different types of specimens is more or less similar for the same displacement. In addition, the maximum value of damage area and tow fractures at full penetration for each specimen is very similar, as well. In the next chapter, a detailed microscopic study clarifies the difference in the damage development for the different types of specimens.
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Macroscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires.

Figure 8.35 – Damage area-displacement response of two-layer woven fabric specimens with and without copper or SMA wires impacted with partial penetration impact tests.

Figure 8.36 – Number of fractured tows-displacement response of two-layer woven fabric specimens with and without copper or SMA wires impacted with partial penetration impact tests.

8.6 Summary

In this chapter, a macroscopic analysis of two layer woven fabric composites with and without copper or SMA wires impacted at different displacement with partial penetration impact tests, in a range of 2mm to 18mm, has been presented. SMA wires showed a better resistance to impact than copper wires, the copper wires all failed in
the impact area for full specimen penetration whereas for the specimen with SMA wires, not all the SMA wires failed.

An approximate measure of the damage area and a measurement of the fracture tows with increasing displacement could not determine any differences between the types of specimens. In the next chapter, Chapter 9, sections of the impacted specimens (for displacements of 2mm to 10mm) are investigated microscopically for damage.
Chapter 9

Microscopic observations of damage in two-layer woven fabric composites with and without copper or SMA wires

9.1 Introduction

Of the two-layer woven fabric specimens, with and without reinforcing copper or SMA wires, were tested with partial penetration impact tests, four different impact displacements were chosen to be investigated in detail for impact displacements in the range of 2mm to 10mm. The cross-sections of these specimens were studied under a microscope and the damage was observed. An Axiophot Zeiss microscope with transmitting light, DIC (differential interference contrast) and an Axiocam camera were used for this analysis.

9.2 Sections under investigation

The specimens were cut at specific points embedded in epoxy and polished, as described in Chapter 3. Two sections were investigated for specimens impacted at a displacement of 7mm and above. The damage on the specimens was classified into two areas; (i) the major damage area, including the centre of impact, and (ii) the stress-whitening area, which is the area surrounding the major damage area and contains stress-whitening. For specimens impacted at a displacement of 7mm and above, these two areas are obvious and therefore two sections were cut for investigation; one at the border of major damage area and stress-whitening area (section A) and the other one at the centre of impact (section B). Figure 9.1 shows
specimen N-07 (a specimen without wires, impacted to 7mm displacement) as an example to identify the two areas and the sections cut from the specimen. The inner circle on the image identifies the major damage area and the outer circle identifies the stress-whitening area. The two lines represent the points were the samples were cut and the arrows indicate the edge of the samples (sections) that were investigated. Letters A and B represent section A and section B, respectively. For specimens with impact displacements less than 7mm, only the section was taken through the centre of impact (section B) was investigated.

![Figure 9.1 - Identification of damage area, stress-whitening area, section A and section B.](image)

During the analysis of the cross-sections, each cross-section was separated into zones, so that it would be easier to identify where the damage was found with respect to the centre of impact. Each zone extends 2mm. The first and last zones of the samples were always discarded because these zones were very close to the edge of the cut specimen. Figure 9.2 shows a sketch of a typical section of a two-layer specimen showing the zones for the microscopy. The schematic shows the specimen separated into seven zones (the actual number of zones varied from sample to sample). The zones are identified by the blue squares, with the zones at the extremities discarded.

![Figure 9.2 - A sketch of a typical division of a cross-section into seven zones.](image)
9.3 Composites without reinforcing wires.

The first set of specimens to be analysed was the two-layer woven fabric specimens without reinforcing copper or SMA wires. Specimen N-02 was partially impacted to a depth of 2mm and the sample taken for analysis was separated into seven zones with the fourth zone covering the middle of the impact area. The damage found in such a low displacement impact was unexpected. Evidence of some of matrix cracks and delaminations were found throughout the sample, in both layers, although the macroscopic analysis (see Chapter 8) had showed no obvious damage on the impact layer, and only stress-whitening on the exit layer. Figure 9.3 shows images from the second zone of specimen N-02 (this zone is about 4mm from the centre of the impact).

![Figure 9.3](image)

Figure 9.3 – Images of a cross-section of specimen N-02, 4mm away from the centre of impact, showing evidence of delamination between warp and weft tows; (a) at both layers and at higher magnification (b) at the exit layer (area b) and (c) at the impact layer (area c).
In Figure 9.3(a), which shows the two woven fabric layers of the specimen there is evidence of delamination between the warp and weft tows in both layers. Figures 9.3(b) (exit layer) and 9.3(c) (impact layer) show these delaminations at higher magnification, at points marked b and c on Figure 9.3(a). Matrix cracks were found in zone 3 of the sample in addition to delaminations (this zone is about 2mm away from the centre of impact). Some of the matrix cracks extended out of the weft bundle into the resin-rich region. It is not certain if these cracks started from the weft bundle and grew into the resin-rich region, but no cracks were found in the resin-rich region without being connected to cracks in the weft bundles; it is therefore more likely that the cracks began in the weft bundles. Examples of these cracks in the exit and impact layer are shown in Figure 9.4, at C, along with other matrix cracks and delaminations.

![Image of a cross-section of specimen N-02, 2mm away from the centre of impact, showing evidence of delamination and matrix cracks.](image)

At the centre of impact region, fibre fracture in addition to delamination and matrix cracks were seen. This area, shown in Figure 9.5 has a highly developed series of matrix cracks and delaminations in the exit layer within the tows, evidence of fibre fracture is shown by dark areas where fractured fibres have been lost during polishing.

The next specimen to be investigated was specimen N-04 that was impacted to 4mm displacement. This specimen was again divided into seven zones, with the centre of the impact being in zone 4. The damage was greater than that found in specimen N-02. For reference, the macroscopic analysis described in Chapter 8 showed the first
evidence of matrix cracks in the exit layer for N-04, whereas only stress-whitening was found in the impact layer.

Figure 9.5 – Images of a cross-section of specimen N-02, at the centre of impact, showing (a) both layers, (b) higher magnification of the exit layer (area b).

Figure 9.6 shows images from zone 2 (4mm away from centre of impact) of specimen N-04. Figure 9.6(a) shows the overall area and the other two images show higher magnification images of the exit layer (Figure 9.6(b), area b) and impact layer (Figure 9.6(c), area c), showing delaminations, matrix cracks and fibre fracture.

Figure 9.7 shows zones 4 and 5 of specimen N-04, which is at the centre of the impact and 2mm away, respectively (note: the two images were placed side by side to be continuous). In these zones, in addition to delaminations, matrix cracks and fibre fractures, cracks extending to the free surface of both layers were found. The fibre fracture seen in specimen N-04 is believed to be caused by the polishing of the sample and not from the impact. Cracks at A and C in Figure 9.7 extend to surface of the impact layer and crack B extends to the surface of the exit layer. Substantial tow fracture can be seen in the impact layer above crack A, which corresponds to the centre of the impact. This area is shown more clearly in Figure 9.8.

As was mentioned earlier, for displacements of 7mm and above, two sections were investigated. Therefore, two sections of specimen N-07 were investigated. One section was on the border of the major damage area (labelled section A) and the stress whitening area, and was about 5mm from the impact centre. The other section was in
the middle of the impact area (labelled section B). In section A, damage was found in the form of matrix cracks and fibre fracture (see Figure 10.9).

Figure 9.6 – Images of a cross-section of specimen N-04, 4mm away from the centre of impact, showing evidence of delamination, matrix cracks and fibre fracture, (a) in both layers and at higher magnification (b) in the exit layer (area b) and (c) in the impact layer (area c).

Figure 9.7 – Image of a cross-section of specimen N-04, at the centre of impact and 2mm away from the centre of impact, showing evidence of delamination, matrix cracks and cracks extending to both free surfaces.
Figure 9.8 – Images of a cross-section of specimen N-04, at the centre of impact, showing a crack at A on the impact layer at higher magnification.

Figure 9.9 – Images of a cross-section from section A of specimen N-07, showing evidence of matrix cracks and fibre fracture.

Heavy damage was found when investigating section B of specimen N-07. As a result of the extensive damage in the specimen, the sample was separated into 11 zones, so that now zone 6 covers the centre of the impact. Figure 9.10 shows the central (sixth) zone. The surface of the exit layer is fractured with severe matrix cracks and delaminations formed, and part of the warp tow in the exit layer is fractured into small pieces. The impact layer, on the other hand, did not suffer as much damage as the exit layer. In the macroscopic analysis a slight deformation of the specimen was seen in the impact area which is clearly related to the fractured exit layer. Also fractured tows
were not found in the macroscopic analysis, but have been seen in the microscopic analysis.

Figure 9.10 – Images of a cross-section from section B of specimen N-07, at the centre of impact, showing the first macroscopic crack.

Figure 9.11 shows the two areas of Figure 9.10, marked as “a” and “b”, at higher magnification. Figure 9.11(a) shows the breakage of the surface of the exit layer (at “a” in Figure 9.10). A part of the matrix region was separated from the weft of the exit layer. The area has much delamination and many matrix cracks. Figure 9.11(b) show that the warp tow of the exit layer (at “b” in Figure 9.10) has much delamination associated with it and the tow has fractured completely.

Figure 9.11 – Images of a cross-section from section B of specimen N-07, at the centre of impact, showing (a) the breakage of the surface and (b) the fibres fractured into pieces, at the exit layer.
The last specimen that was examined without wires was N-09, which was impacted at a displacement of 9mm. As with the previous specimen, two sections from this specimen were investigated as well. Section A is 10mm away from the centre of impact and section B is at the centre of impact. In section A of specimen N-09, more damage was found than in section A of specimen N-07. The number of delaminations, matrix cracks and fibre fracture had increased. In some cases, the matrix cracks reached the surface of the exit layer (at C for example in Figure 9.12).

Figure 9.12 – Images of a cross-section from section A of specimen N-09, showing evidence of matrix cracks and fibre fracture.

Section B of specimen N-09 was separated into nine zones with the fifth one at the middle of the impact area. During the macroscopic analysis of this specimen, the consequence of a small penetration of the specimen could be seen. Figure 9.13 shows that the impact and exit layer are heavily deformed. This penetration of the specimen is believed to be the cause of the sudden drop of load in the load-displacement plot (Figure 6.11(c)). Damage in section B was greater than in section B of specimen N-07. Figure 9.13 shows the centre of impact of the specimen. The arrow in the figure shows the point of impact. The matrix region in the centre of impact was fractured in both layers. The warp tow in the impact layer was fractured and the tow in the exit region had suffered significant damage. The macroscopic analysis had also shown failed tows in the impact layer (Figure 8.7).
The damage was spread around the centre of the impact, as well. Figure 9.14 shows a composite image of three zones, the centre of impact and two zones either side. The zones either side of the centre of impact contain a large number of delamination, matrix cracks and fibre fractures, with cracks extending to the surface of both layers. The cracks extending to the surface of the impact layer (at C) are about 1mm apart and it is believed that these cracks are the circular cracks within the impact layer seen in the macroscopic analysis of the specimen (Figure 8.7).

Figure 9.13 – Images of a cross-section from section B of specimen N-09, at the centre of impact, showing the initiation of penetration.

Figure 9.14 – Image of a cross-section from section B of specimen N-09. The arrow shows the point of impact.
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9.4 Composites with reinforcing copper wires.

Specimens with reinforcing copper wires impacted at different impact displacements were investigated in the same way as the specimens without wires. Specimen C-02 was separated into nine zones, with the fifth zone being at the middle of the impact area. Although the macroscopic analysis in Chapter 8 found no damage in the specimen, except stress-whitening in the exit layer, the damage that was found using the microscopic analysis is very similar to the specimen without wires (specimen N-02). Figures 9.15(a) and 9.15(b) shows images of the cross-section at the centre of impact. The white circle in Figure 9.15(a) is a copper wire. Evidence of delaminations and matrix cracks were found in both the exit and impact layers (at A and B, for example). No evidence was found of debonding or any kind of damage to the copper wire or the surrounding matrix.

![Figure 9.15 - Images of a cross-section of specimen C-02, at the centre of impact, showing evidence of delaminations and matrix cracks; (a) in both layers and (b) at higher magnification in the impact layer (area b).](image)

For specimen C-05, which was subjected to a displacement of 5mm, the damage on the specimen was greater than that of specimen C-02, but not significantly different to specimen N-04 (without wires). The macroscopic analysis had shown matrix cracks only in the exit layer, but the microscopic analysis found matrix cracks within the impact layer as well. Delaminations, matrix cracks (a few extending to the surface) were also found. No evidence was found to suggest any damage or debonding of the copper wires from the surrounding matrix. Figures 9.16(a) to 9.16(c) show images of
the damage in specimen C-05 at the centre of impact. The white line in Figure 9.16(a) is a copper wire. Figure 9.16(b) shows matrix cracks and delaminations in the impact layers at higher magnification. Figure 9.16(c) shows no debonding around a copper wire.

Figure 9.16 – Images of a cross-section of specimen C-05, 6mm away from the centre of impact, (a) showing evidence of delaminations, matrix cracks and fibre fracture in both layers and (b) the impact layer (area b) and (c) an undamaged wire (area c).

Specimen C-08 was impacted to a displacement of 8mm which is a displacement after the sudden drop of load in the load-displacement curve. Two sections of specimen C-08 were investigated. Section A is 10mm away from the centre of impact and section B is at the centre of impact. Figures 9.17(a) to 9.17(c) shows images of section A. Fibre fractures within a tow and matrix cracks could be seen in the impact layer. Figures 9.17(b) and 9.17(c) show examples of delaminations and matrix cracks for the impact and exit layer, respectively.
Section B was separated into 13 zones, with the seventh zone in the middle of the impact area. Heavy damage was found throughout section B (Figure 9.18) which is believed to be related to the sudden drop of load in the load-displacement plot. In the middle of the impact area, the specimen was partially penetrated. Debonding of the copper wires and substantial matrix cracks extending to the copper wires were found. Some copper wires were completely debonded from the rest of the specimen. The macroscopic analysis discussed in Chapter 8 showed a slight deformation of the specimen, including the copper wires, without suggesting the heavy damage that was found microscopically.

Figure 9.17 - Images of a cross-section from section A of specimen C-08, showing evidence of delaminations, matrix cracks and fibre fracture: (a) in both layers; (b) in impact layer (area b); (c) in exit layer (area c).

Figure 9.18(a) shows an overview of the central impact area and the heavy damage that the specimen suffered is obvious and Figure 9.18(b) shows part of this image at
higher magnification; the warp tow of exit layer is fractured, and the weft taws are separated from the surrounding matrix. The two wires in the middle of the impact area are deformed and debonded from the rest of the specimen and the wire extending from left to right (white line in the image) is also clearly deformed. Figure 9.18(c) shows the failure of a warp tow in the exit layer in the middle of the impact area. Failure of the taws had already been seen in the macroscopic analysis of the specimen (Figure 8.15). The dark regions in Figure 9.18 are probably sections of composite which were fractured and delaminated during the impact, and were then separated and lost during the polishing process. Although difficult to quantify, the damage in the specimen seems to be greater than for the specimen without wires (specimen N-07); in specimen N-07, major damage appeared only in the exit layer, whereas here the deformation is in the impact layer as well.

![Figure 9.18](image)

**Figure 9.18** – Images of a cross-section from section B of specimen C-08, at the centre of impact, showing the initiation penetration of the specimen at different magnification.
The final specimen to be investigated under the microscope with reinforcing copper wire was specimen C-10, impacted at a displacement of 10mm which was investigated in two areas (as for the previous specimen). Section A is 12mm away from the centre of impact and section B is at the centre of impact. Looking at section A of this specimen, more damage was found than the equivalent section A of specimen C-08. Figure 9.19 shows a matrix crack which has partly debonded two wires, extends though a resin-rich region, and delaminates warp tows in both the exit and impact layers.

Figure 9.19 – Images of a cross-section from section A of specimen C-10, showing evidence of damage around the copper wires.

Figure 9.20 shows a composite image from the centre of impact in section B and 2mm from the impact centre for specimen C-10. In Figure 9.20, the penetration of the specimen can be seen with all the warp tows of the two layers and the matrix region fractured. Heavy damage can be seen in the area surrounding the impact centre and also 2mm away where the weft tows of the two layers were debonded from the matrix region. Figure 9.21 show a cross-section of specimen C-10 6mm away from the centre of impact in section B. The cracks on the impact layer are about 1mm apart and it is believed that these cracks are the circular cracks seen in the macroscopic analysis of the specimen (Figure 8.19).

Finally, measurements were made from the images of the impacted specimens of the diameter of the wires inside the damage area of the specimen. It was found that the diameter of the wires remained at 0.152±0.001 mm for all the impact displacements.
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up to 10mm, with an exception of the two copper wires in Figure 9.18, suggesting that most of the wires measured did not suffer plastic deformation.

Figure 9.20 – Image of a cross-section from section B of specimen C-10, at the centre of impact and 2mm away from the centre of impact, showing the penetration and damage formed on the specimen.

Figure 9.21 – Image of a cross-section from section B of specimen C-10, at (a) 6mm away from the centre of impact showing the circular cracks seen in the macroscopic analysis.

9.5 Composites with reinforcing SMA wires.

Sections of specimens with reinforcing SMA wires were also examined under the microscope. For specimen S-02, impacted to a displacement of 2mm, the macroscopic analysis (Chapter 8) suggested there were no matrix cracks in either layer, but microscopy revealed evidence of delaminations and matrix cracks. In general, the damage was
similar with the other types of specimens (i.e. with and without reinforcing copper wires). The damage was mainly found in the weft tows closest to the free surface of both layers. The SMA wires were unaffected by the impact and no evidence of damage was found around them. Figure 9.22 shows images from the impact centre of specimen S-02. Figure 9.22(a) shows the area at low magnification and Figure 9.22(b) is a magnification of area b, showing delaminations and matrix cracks in the weft tows of the impact layer (note: the SMA wires appeared to be black because a different contrast on the microscope was used to get a better view of the damage). Figure 9.22(c) shows no debonding of the SMA wires.

![Figure 9.22 - Image of a cross-section of specimen S-02, at the centre of impact showing (a) the two layers; (b) evidence of delaminations and matrix cracks in the impact layer (area b); and (c) no damage around an SMA wire.](image)

Specimen S-05 showed more delaminations and matrix cracks than the equivalent specimens without SMA wires. Furthermore, some debonding was found around some of the SMA wires. Figure 9.23 shows images of a cross-section from specimen
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S-05 at a displacement of 2mm from the impact centre. The damage is obvious even in Figure 9.23(a) at low magnification. Figure 9.23(b) and 9.23(c) show a higher magnification of areas b and c. In Figure 9.23(b), a matrix crack from the warp tow of the exit layer can be seen extending to the surface. Figure 9.23(c) shows matrix cracks and delaminations associated with the weft tow of the exit layer. Figure 9.24 shows the SMA wire from Figure 9.23(a) at higher magnification where debonding of the wire from the matrix can be seen.

As mentioned above, part of the matrix region in the exit layer was fractured at the centre of impact. This is shown on the image in Figure 9.25(a) which also shows a matrix crack extending from the warp tow of the exit layer to an SMA wire through the matrix region (Figure 9.25(b)).

![Figure 9.23](image)

**Figure 9.23** – Images of a cross-section of specimen S-05, 2mm away from the centre of impact, showing evidence of delaminations, matrix cracks and fibre fracture; (a) shows both layers; (b) the exit layer (area b); and (c) at both layers (area c).
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Figure 9.24 – Image of a cross-section of specimen S-05, 2mm away from the centre of impact, showing evidences of debonding, around the SMA wire.

Figure 9.25 – Cross-section of specimen S-05, at the centre of impact showing (a) evidences of matrix breakage and (b) debonding around the SMA wire (area b).

Two sections of specimen S-08 were investigated. Section A which is 8mm away from the impact centre, showed small amounts of damage in the form of delaminations, matrix cracks and fibre fracture. Figure 9.26 shows an image of a part of section A showing delaminations and matrix cracks.

Section B, in the middle of the impact area, showed less damage than the equivalent specimens with and without reinforcing copper wires. The permanent deformation of the specimen and the damage found in the exit layer was much less than the other two specimens. Tow fractured into small pieces were found in the middle of the impact area but less damage in the tows was found than in the equivalent zone of specimen
C-08. Debonding was found around the SMA wires although the wires were undeformed.

Figure 9.26 – Image of a cross-section from section A of specimen S-08, showing evidence of delaminations, matrix cracks and fibre fractures.

Figure 9.27 shows images from zones close to the impact area of specimen S-08, 2mm away from the impact centre on the left and at the centre of impact on the right. In Figure 9.27(a) heavy damage can be seen with a small permanent deformation of the exit layer, which caused the specimen to deformed macroscopically. Parts of the specimen at the free surface of the exit layer have fractured and debonding of the SMA wire can be seen. Figure 9.27(b) shows fractured fibres in a tow in the exit layer, indicated by point b in Figure 9.27(a). Figure 9.28, which show areas 2mm and 4mm away from the centre of impact, show delaminations and matrix cracks associated with all the tows, fibre fractures in both layers and debonding of the SMA wires.

Specimen S-10 was also investigated in two areas, 13mm from the impact centre (section A) and in the impact centre (section B). Section A of the specimen showed damage in the form of delaminations, matrix cracks and tow fractures similar to damage seen in section A of specimen S-08. By contrast, section B (at the impact centre) showed more damage with respect to the development of penetration than the equivalent view of specimens C-10 and N-10. Specimen S-10 was completely penetrated at the middle of the impact area of the specimen and some SMA wires
were debonded from the rest of the specimens. None of the cross-sections of the SMA wires examined appeared deformed. The macroscopic analysis of this specimen showed a small penetration of the specimen without suggestion a full penetration.

Figure 9.27 – Images of a cross-section from section B of specimen S-08, (a) 2mm away from the centre of impact and at the centre of impact and (b) at higher magnification the exit layer (area b), showing evidences of delaminations, matrix cracks, fibre fracture and damage around the SMA wires.

Figure 9.29 shows an image of a cross-section from section B, 6mm away from the centre of impact. Two cracks are seen to extend to the free surface of the impact layer are at a distance of 1mm apart which are believed to be the circular cracks seen in the macroscopic analysis (Figure 8.29(d)). Figure 9.30 shows the centre of impact of specimen S-10. The penetration of the specimen and the severe damage that the specimen suffered is clear. The warp tows of both layers have fractured, with severe
damage to the weft tow of the impact layer. The SMA wires have debonded from the specimen.

The diameters of the SMA wires inside the central damaged area of the specimens were measured and it was observed that the diameter had decreased from 0.152 mm to about 0.144±0.001 mm. This indicates that the wires were plastically deformed without fracturing whereas the copper wires failed at lower strains.

Figure 9.28 – Images of a cross-section from section B of specimen S-08, 2mm and 4mm away from the right side of the centre of impact, showing evidences of delamination, matrix cracks and fibre fracture.

Figure 9.29 – Image of a cross-section from section B of specimen S-10, 6mm away from the centre of impact, showing the circular cracks seen in the macroscopic analysis.
9.6 Comparison of damage observations for the three types of specimens

Table 9.1 shows a summary of the macroscopic and microscopic observations on damage for the three different types of two-layer specimens at the different impact displacements. Specimens with and without copper or SMA wires showed similar damage when impacted at a displacement of 2mm. Matrix cracks and delaminations were found in both the impact and exit layers. The copper and SMA wires were unaffected by the impact, without any debonding between the wires and the surrounding matrix. It is possible that stress whitening was macroscopically visible in the exit layer but not in the impact layer because the exit layer was subjected to tension that led to the tows showing visible stress whitening, whereas the impact layer was subjected to compression.

Similarly to specimens impacted to 2mm, the different types of specimens showed similar damage when impacted to a displacement of 4mm or 5mm. More extensive matrix cracks, delaminations and matrix cracks extending to the surface of both layers were found. No debonding was found around the copper wire and the surrounding matrix whereas debonding was found around the SMA wire and the surrounding matrix. This is believed to be due to the expansion of the SMA wire which caused friction between the SMA wire and the matrix.
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<table>
<thead>
<tr>
<th>Displacement mm</th>
<th>Damage on specimens without reinforcing wires</th>
<th>Damage on specimens with reinforcing copper wires</th>
<th>Damage on specimens with reinforcing SMA wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Small amount of delaminations &amp; matrix cracks in both layers.</td>
<td>Small amount of delaminations &amp; Matrix cracks. No debonding of wires.</td>
<td>Similar damage to N-02 and C-02. No debonding of wires.</td>
</tr>
<tr>
<td>12</td>
<td>Increased deformation and penetration forming a cross of fractured tows.</td>
<td>Increased penetration. Fractured wires.</td>
<td>Increased deformation and penetration. First fractured wires.</td>
</tr>
<tr>
<td>18</td>
<td>Full penetration</td>
<td>Full penetration. All wires failed.</td>
<td>Full penetration. Not all wires failed.</td>
</tr>
</tbody>
</table>

Table 9.1 – Summary of the main damage of the three different types of specimens at the seven different impact displacements investigated.

Permanent deformation was observed on all types of specimens impacted to 7mm or 8mm. Microscopy suggests this is due to tow and matrix fracture at the centre of impact of the specimens. Circular cracks were found in the impact layer of all types of specimens. The radius of the inner circle was around 4mm and the cracks were about 1mm apart for specimens with and without copper wires and the inner circle radius for specimens with SMA wires was about 4.7mm and the cracks were about 2mm apart.
Evidence of permanently deformed copper wires was found, but SMA wires appear to be unaffected. Copper and SMA wires had debonded from the surrounding matrix.

For impact displacements of 9mm and 10mm, tow fractures, matrix cracks and delaminations in both layers of all specimens were found. All specimens showed through-thickness cracking. The circular cracks on the impact layer had an inner circle radius of about 4mm and the cracks were about 1mm apart for all types of specimens. Evidence of fractured copper wires was found, whereas no SMA wire failed, although some SMA wires were permanently deformed. The diameter of the wires was measured from specimens impacted at 2mm to specimens impacted at 10mm and it was noticed that most of the copper wires had a constant diameter of 0.152mm, whereas the diameter of the SMA wires decreased from 0.152mm to 0.144mm.

All types of specimens impacted at 12mm showed a cross-shaped through-thickness crack. Most of the copper wire in the damage area failed and the first evidence of the failure of SMA wires was found. At impact displacements of 15mm to 18mm full penetration was reached for all specimens. All the copper wires in the damage area failed but this was not the case for the SMA wires where few of the wires failed and some of them deformed.

9.7 Summary

In this chapter, the microscopic observations of specimens with and without copper or SMA wires impacted with partial impact tests for displacements of 2mm to 10mm were discussed. Combined with the macroscopic observations from the previous chapter (Chapter 8), a history of the damage growth of the specimens has been developed. Microscopic analysis of the different types of specimens revealed evidence that was not expected when analysing the specimens at the macroscopic level. The most surprising aspect was that damage was found in all three types of specimens, after impact displacements of only 2mm, in the form of matrix cracks and delaminations. The damage increased as the displacement increased and the penetration of the specimens began from an impact displacement of about 8mm. In
the next chapter (Chapter 10) the results of a limited study on the impact of cross-ply glass fibres/epoxy composites are presented.
Chapter 10

A limited study on the controlled impact of cross-ply grass/epoxy laminates

10.1 Introduction

In order to investigate whether the energy expression developed by Martello et al (2006) and relating impact energy, absorbed energy and penetration energy is also applicable to glass fibre/epoxy cross-ply laminates, a limited impact study on cross-ply laminates materials has been carried out. Glass fibre/epoxy cross-ply laminates [0/90], were manufactured and impact tested as described in Chapter 3. In this chapter the results from impact testing of these laminates, having a nominal ply thickness of 0.25mm, will be presented. These results can also be compared with results of impact testing of similar cross-ply laminates with a nominal ply thickness of 0.5mm [Stone 2007].

10.2 Impact test results of cross-ply glass/epoxy composites

The cross-ply specimens with 0.25mm nominal ply thickness were tested in a servo-hydraulic testing machine with partial penetration impact tests at a velocity of 0.08mmsec\(^{-1}\). The specimens had a measured volume fraction of 0.5±0.03, considerably higher than the woven fabric composites (V\(_f\) of about 0.4). Young’s modulus was calculated to be 20.3GPa, based on the rule-of-mixtures, and the measured Young’s modulus of two specimens was 20.0GPa and 20.6GPa,
respectively. The impact displacements used were between the range of 2mm-24mm. Figure 10.1 shows the load-displacement response of fourteen cross-ply specimens impacted in that impact displacement range, designated CPF-02 to CPF-24, where the numbers indicate the displacement.

![Load-displacement response of fourteen cross-ply specimens](image)

**Figure 10.1 – Load-displacement response of fourteen cross-ply specimens, with 0.25mm nominal ply thickness, impacted with partial penetration impact test at different impact displacements.**

The initial load-displacement response of all the specimens up to 5mm was roughly the same. After 5mm displacement, the specimens showed peak loads which differed considerably. The range of the peak load was 0.79kN to 1.65kN. After the peak load many specimens did not show a sudden drop of load, as seen with the woven fabric composites, but few did. The cross-ply specimens were not fully penetrated by the impactor at 18mm as seen with all the woven fabric specimens, but a displacement of 24mm in displacement was needed for full penetration. The increase in the load at a displacement of 24mm for specimen CPF-24 was due to the impactor being forced to pull out of the specimen during unloading.

Due to the large number of specimens tested, comparing the load-displacement plots together is not clear; therefore the plots were separated depending on the thickness of the specimens. Figure 10.2 shows four graphs and each graph compares the load-displacement plots of the specimens with similar thickness. The thicknesses of the
specimens were separated into four groups; under 1mm (Figure 10.2(a)), between 1mm and 1.2mm (Figure 10.2(b)), between 1.2mm and 1.4mm (Figure 10.2(c)) and above 1.4mm (Figure 10.2(d)). Comparing the load-displacement response for each thickness group, it can be seen that the results are roughly similar between them with an exception specimen CPF-11 which has a much lower peak load (0.87kN) than specimen CPF-24 (1.17kN) and also specimen CPF-11 does not experience a sudden drop of load after the peak load is reached whereas specimen CPF-24 does.

Figure 10.2 – Load-displacement response of cross-ply specimens, with 0.25mm nominal ply thickness, impacted with partial penetration impact test at different impact displacements, with thicknesses (a) under 1mm, (b) between 1mm-1.2mm, (c) between 1.2mm-1.4mm and (d) above 1.4mm.

Table 10.1 below shows the impact displacement, the peak load, the thickness and the energy absorbed during impact for all the cross-ply specimens. The thicknesses of the specimens were in a range of 0.95mm to 1.59mm. The energy needed to fully penetrate the cross-ply specimens was about 9.3J.
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A limited study on the controlled impact of cross-ply glass/epoxy laminates.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Impact Displacement (mm)</th>
<th>Peak load (kN)</th>
<th>Thickness (mm)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPF-02</td>
<td>2.4</td>
<td>0.14</td>
<td>1.13</td>
<td>0.01</td>
</tr>
<tr>
<td>CPF-04</td>
<td>3.9</td>
<td>0.36</td>
<td>1.03</td>
<td>0.08</td>
</tr>
<tr>
<td>CPF2-04</td>
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<td>0.47</td>
<td>1.2</td>
<td>0.17</td>
</tr>
<tr>
<td>CPF-05</td>
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<td>0.72</td>
<td>1.11</td>
<td>0.21</td>
</tr>
<tr>
<td>CPF-06</td>
<td>5.6</td>
<td>0.79</td>
<td>1.21</td>
<td>0.33</td>
</tr>
<tr>
<td>CPF-07</td>
<td>7</td>
<td>1.15</td>
<td>1.03</td>
<td>1.12</td>
</tr>
<tr>
<td>CPF-08</td>
<td>8.3</td>
<td>1.25</td>
<td>1.16</td>
<td>3.09</td>
</tr>
<tr>
<td>CPF-10</td>
<td>10</td>
<td>1.4</td>
<td>1.28</td>
<td>4.8</td>
</tr>
<tr>
<td>CPF-11</td>
<td>10.8</td>
<td>0.87</td>
<td>1.53</td>
<td>4.12</td>
</tr>
<tr>
<td>CPF-12</td>
<td>12.3</td>
<td>1.35</td>
<td>1.16</td>
<td>5.92</td>
</tr>
<tr>
<td>CPF2-12</td>
<td>12.2</td>
<td>1.42</td>
<td>1.13</td>
<td>7.4</td>
</tr>
<tr>
<td>CPF-13</td>
<td>13.2</td>
<td>1.65</td>
<td>0.95</td>
<td>9.2</td>
</tr>
<tr>
<td>CPF-18</td>
<td>18.4</td>
<td>1.25</td>
<td>1.2</td>
<td>7.37</td>
</tr>
<tr>
<td>CPF-24</td>
<td>24</td>
<td>1.17</td>
<td>1.59</td>
<td>9.02</td>
</tr>
</tbody>
</table>

Table 10.1 - Impact displacement, peak load, thickness and the energy absorption of cross-ply specimens with 0.25mm nominal ply thickness.

A video camera was also used to record the impact experiments of the cross-ply specimens, as was done with the impact experiments on woven fabric specimens. Figure 10.3 shows images taken from the impact of cross-ply specimens. The images were extracted at the maximum displacements of six specimens, impacted at 2mm, 5mm, 8mm, 12mm, 18mm and 24mm. For reference, the load-displacement response shown in the figure is from the specimen CPF-24, though it should be remembered that the load-displacement responses different from specimen to specimen (e.g. peak load). No damage can be seen in Figure 10.3(a) which was impacted to 2mm. The specimen in Figure 10.3(b) was impacted to 5mm and a small delamination between the 0° and 90° plies was formed in the middle of the impact area, even though is not shown clearly in the image. This damage is shown at D on the figure. The damage of Figure 10.3(c) is clear. Impacted to 8mm, delaminations at E can be seen (which are at the upper 0/90 interface) and matrix cracks in the exit 0° ply at F. Although it cannot be seen in the figure, the fibres in all plies at the middle of the impact of the specimen fractured causing the sudden drop of load (for some specimens) in the load-displacement graph and forming a small through-thickness penetration. Figures 10.3(d)-10.3(f) shows the penetration of the specimens by the impactor and the growth of the damage around the penetrated area, with delamination expanding away from the impact centre and the fibres in the plies failing forming a cross-shape.
penetration as the impactor was driven into the specimens until full penetration was reached. The last image, Figure 10.3(g), was taken with the impactor removed from the specimen.

Figure 10.3 – Load-displacement response of a cross-ply specimen with 0.25mm nominal ply thickness, with corresponding images from cross-ply specimens impacted at different impact displacements in partial penetration experiments.

Figure 10.4 shows additional images of specimens impacted to displacements of 4mm (Figure 10.4(a)) and 7mm (Figure 10.4(b)). These low-displacement images show the growth of peanut-shaped delamination damage which is common for cross-ply specimens [Abrate, 1991].
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A limited study on the controlled impact of cross-ply glass/epoxy laminates.

Figure 10.4 – Images of cross-ply specimens with 0.25mm nominal ply-thickness, after impact displacement to (a) 4mm and (b) 7mm.

10.3 Comparison with results on a cross-ply laminate with thicker plies

The impact response of cross-ply specimens with 0.25mm nominal ply thickness have been compared with the equivalent response of similar cross-ply specimens with 0.5mm nominal ply thickness tested by Stone (2007). Table 10.2 shows the impact displacement, the peak load, the thickness and the energy absorbed during impact of the cross-ply specimens tested by Stone (2007). These specimens required about 24.4J to be fully penetrated.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Impact Displacement (mm)</th>
<th>Peak load (kN)</th>
<th>Thickness (mm)</th>
<th>Energy Absorption (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone-02</td>
<td>2</td>
<td>0.51</td>
<td>2.34</td>
<td>0.04</td>
</tr>
<tr>
<td>Stone-06</td>
<td>6.1</td>
<td>2.74</td>
<td>2.39</td>
<td>2.25</td>
</tr>
<tr>
<td>Stone-06.5</td>
<td>6.5</td>
<td>2.39</td>
<td>2.07</td>
<td>2.16</td>
</tr>
<tr>
<td>Stone-08</td>
<td>8.7</td>
<td>3.12</td>
<td>2.39</td>
<td>8.65</td>
</tr>
<tr>
<td>Stone-11</td>
<td>10.9</td>
<td>2.65</td>
<td>2.22</td>
<td>13.23</td>
</tr>
<tr>
<td>Stone-14</td>
<td>14</td>
<td>3.12</td>
<td>2.25</td>
<td>23.15</td>
</tr>
<tr>
<td>Stone-16</td>
<td>16</td>
<td>2.9</td>
<td>2.43</td>
<td>23.44</td>
</tr>
<tr>
<td>Stone-18</td>
<td>17.8</td>
<td>3.43</td>
<td>2.49</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Table 10.2 – Impact displacement, peak load, thickness and the energy absorption of cross-ply specimens with 0.5mm nominal ply thickness.

Figure 10.5 shows comparisons of the load-displacement response of the cross-ply specimens with the two different nominal ply thicknesses. The load-displacement
trends of the specimens are very similar and as expected, the thicker specimens are stiffer than the thinner specimens. It can be seen that the thicker specimens also do not always show a sudden drop of load after the peak load.

Figure 10.5 – Comparison of load-displacement responses between cross-ply specimens with 0.5mm and 0.25mm nominal ply thicknesses at (a) 2mm, (b) 6mm, (c) 8mm, (d) 11mm and (e) 18mm in partial penetration impact experiments.

The values of peak load and of the absorbed energy of the thicker specimens were around three times higher that the equivalent values of the thinner specimens for the
same impact displacement (the only exception the value of the absorbed energy was specimen Stone-06 which was seven-times higher than the equivalent value of specimen CPF-06). This is consistent with the literature where many researchers [e.g. Davies and Zhang 1995; Davies et al 1996; Schoeppner and Abrate 2000; Caprino et al 1999] reported that the peak load of a specific material is proportional to thickness to the power of 1.5. The Stone (2007) specimens have about double the thickness of the CPF specimens and, therefore, the peak load should be about three times higher than for the CPF specimens. If the curves have similar shapes, it would be expected that the energy absorbed would be three times higher as well.

10.4 Energy analysis

The impact and absorbed energies of the cross-ply specimens, with 0.25mm nominal ply thickness, were measured from the load-displacement graphs, as it was done with the woven fabric specimens, and the data was tested against the empirical relationship, Equation 2.5, suggested by Martello and colleagues (2006):

\[
\frac{U_{\text{abs}}}{U_p} = \left( \frac{U_{\text{imp}}}{U_p} \right)^2
\]  

(2.5)

The penetration energy was taken as the energy needed to fully penetrate specimen CPF-24. Figure 10.6 shows the normalised absorption coefficient-impact intensity coefficient response of the specimens. A reference line, using Equation 2.5, is added for direct comparison with the results. The data show a good agreement with Equation 2.5 although the region between 0.4 < \frac{U_{\text{imp}}}{U_p} < 0.8 has a slightly higher value of absorption coefficient than Equation 2.5 suggests (this was already been seen in the results for the woven fabric specimens in Chapter 7).

Figure 10.7 shows two log-log plots of this cross-ply laminate data. Figure 10.7(a) shows data for all the specimens suggesting a power of 1.6, whereas Figure 10.7(b) separates the data into three suggesting powers was of 1.7, 1.5 and 1.6. Hence, it is reasonable to conclude the exponent is within the range of 1.5 and 2. A similar
analysis for the Stone (2007) data (Figure 10.8) reaches the same conclusions. Overall, then, it can be seen that the analysis of the impact/absorption energies for the cross-ply specimens is in agreement with the relationship suggested by the analysis of energy for the woven fabric specimens i.e. $\frac{U_{abs}}{U_p} = \left( \frac{U_{imp}}{U_p} \right)^\alpha$ where $\alpha$ lies between 1.5 and 2.

![Graph](image)

**Figure 10.6** – Absorption coefficient-impact intensity coefficient response for cross-ply specimens with 0.25mm nominal ply thickness.

![Logarithmic Graph](image)

**Figure 10.7** – Logarithmic of absorption coefficient-logarithmic of impact intensity coefficient responses for cross-ply specimens with 0.25mm nominal ply thickness.
In this chapter impact experiments on cross-ply (0/90)ₜ specimens with 0.25mm nominal ply thickness, have been described. The specimens were impacted with partial penetration impact tests. The load-displacement response was not consistent for all the specimens, with some specimens showing a sudden drop of load after their peak load but others that did not. The damage of the cross-ply specimen is in a form of cracks, delaminations and fibre failure. The peanut-shaped delamination damage mentioned in the literature was seen in these specimens for low impact displacements, and a rhombus-shaped damage was seen for the higher impact displacements.
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When these specimens were compared with thicker cross-ply specimens tested by Stone (2007), having a 0.5mm nominal ply thickness, it was found that the peak load and the absorbed energy of the Stone (2007) specimens were, in general, three times higher that the thinner specimens, which is consistent with the peak load-thickness relationship suggested in the literature.

For the normalised absorption coefficient-impact intensity coefficient response, showed a good agreement with the expression $\frac{U_{abs}}{U_P} = \left( \frac{U_{imp}}{U_P} \right)^{\alpha}$ where $\alpha$ lies between 1.5 and 2, as had been found earlier for the woven fabric specimens.

The next chapter, Chapter 11, is the concluding remarks of the present project and suggested future work based on this work.
Chapter 11

Conclusions and future work

11.1 Conclusions

During this project a method of controlled impact testing has been developed. A specially designed impact rig was installed within a servo-hydraulic testing machine with a spherical glass impactor that was driven into the specimens at a constant speed. A video camera enabled the development of damage within the transparent specimens to be observed.

Two types of glass reinforced architectures were used for this project: eight-, four- and two-layer woven fabric specimens (with and without reinforcing copper or shape-memory alloy wires) and cross-ply laminates, [0/90], with 0.25mm nominal ply thickness, unidirectional plies. Both types of glass-reinforced laminates were made with a tri-component epoxy resin. Three different types of impact tests were performed: single impact tests where the impactor is driven completely through the specimen; multiple impact tests where the impactor is driven to a certain displacement, withdrawn, and then driven to a higher displacement, up to complete specimen penetration; and partial penetration impact tests, for which the impactor is driven to a single displacement, short of complete penetration, and then withdrawn. In general, the overall load-displacement response for a multiple impact test was very similar to a single impact or a partial penetration impact test. In all cases, the load-
displacement response could be used to measure impact energy and absorbed energy of a test.

In the first tests, eight-layer woven fabric specimens without wires were tested at three different velocities so an appropriate velocity for subsequent experiments could be found (4mmsec\(^{-1}\) was used). Eight-layer woven fabric specimens, with and without copper or SMA wires with a volume fraction of 0.01, were impacted at 4mmsec\(^{-1}\) and compared. The specimens with reinforced copper or SMA wires showed improved impact properties over the specimens without wires. However, there were no major differences between the results for SMA and copper wire reinforcements and therefore it was decided to increase the volume fraction of the wires by decreasing the number of layers of woven fabric layers from eight to four. Finally, specimens with two-layer woven fabric layers were used as these showed the clearest results, and these specimens were subjected to the three types of impact test mentioned above. Damage was also investigated macroscopically and microscopically.

Two-layer woven fabric composites, with and without copper or SMA wires, were impacted to different displacements with partial penetration impact tests and the three types of composites showed similar damage development. The macroscopic damage area increased as the impactor displacement into the specimen increased, and the values of the maximum damage area of the three types of composites were quite close. However, this very approximate measure of damage does not represent the actual damage in the specimen which can only be determined through microscopy on polished sections. Although not visible macroscopically, damage was found in all three kinds of specimens after impact displacements of only 2mm; the damage consisted of matrix cracks and delaminations. The damage increased as the displacement increased and the through-thickness penetration of the specimens started from an impactor displacement of about 8mm. Even at low impact displacements, damage was found around SMA wires, which was not the case around the copper wires. In general SMA wires showed a better impact performance than copper wires in the sense that all the copper wires failed in the impact area when the specimen with copper wires was penetrated, whereas not all the SMA wires failed. Samples of the copper and SMA wires used for the impact test were tensile tested. Comparing the
two wires it was clearly seen that the energy needed to fail the SMA wire was more than four times higher than the energy expended to fail the copper wires.

The volume fraction of the components of the different layers of the woven fabric specimens, with and without reinforcing copper or SMA wires, was measured by performing a burn-off test on four samples of each kind of specimens. The Young's modulus of each type of composite was predicted by treating the woven fabric composites as cross-ply laminates with two extra layers for the wires, one for each direction, if necessary. The predicted values agreed with the experimental values for all composites wires within 10%, with the exception of the four-layer woven fabric composite with SMA wires, which agreed within 15%.

In addition to the tests on woven fabric composites, impact experiments were also performed on cross-ply (0/90)\textsubscript{s} specimens with 0.25mm nominal ply thickness. The specimens were impacted with partial penetration impact tests and it was found that the load-displacement response was not consistent for all specimens. Some of the specimens showed a sudden drop of load after the peak load, but others did not. When these results were compared with results from another researcher on cross-ply specimens with 0.5mm nominal ply thickness, it was found that the peak load and the absorbed energy of the thicker specimens were about three times higher that the thinner specimens tested here, which is consistent with suggestions in the literature.

For all specimens tested using the low-velocity impact rig, the load-displacement results during an impact test could be used to find the impact energy (\( U_{\text{imp}} \)), absorbed energy (\( U_{\text{abs}} \)) and penetration energy (\( U_p \)) for the test. With regard to the energies, the data from the multiple impact tests, and from the partial penetration impact tests, showed a good agreement with an empirical relationship that Martello and colleagues (Martello et al, 2006) have suggested i.e. \( \frac{U_{\text{abs}}}{U_p} = \left( \frac{U_{\text{imp}}}{U_p} \right)^\alpha \) where \( \alpha \) lies between 1.5 and 2 (Martello and colleagues suggested \( \alpha=2 \)). This relationship was obeyed by all the specimen types tested in this work.
Based on the impact results from tests on specimens with and without copper and SMA additional wire reinforcement, it has been concluded overall that the benefit of using superelastic SMA wires is achieved for impacts which produce through-thickness penetration of the specimens, when the large energy absorbing characteristics of the wires are used, and when the volume of the SMA wires is high.

**11.2 Future work**

With respect to the present project, some suggestions can be made for the continuation of this work. Within this project, it has been seen that only composites with the highest volume fraction of SMA wire reinforcement showed improvements on impact resistance compared to the composites without SMA wires or composites with copper wires. Consequently, it would be useful to test coupons with higher than the volume fraction of SMA wire than used here, so that the most suitable volume fraction can be found that gives the best results with respect to impact resistance. With regard to the relationship found between the energies, it is important to establish whether this is a universal relationship, or whether it is affected by, for example, the shape of the indenter. Consequently, different types of impactor geometries should be tested, such as sharp impactors instead of spherical ones, to see whether the empirical expression is changed for a different impactor shape. As was seen in this study the SMA wires are useful at high displacements. It be interesting to see if the wires are more helpful if layers of SMA wires introduce in composites which are already pre-strain at about 4% (at the beginning of the plateau). Therefore, the SMA wires are already changing into stress-induce martensite.

Through this work a good understanding of the damage development in the two-layer woven fabric specimens, with and without copper or SMA wires, has been established. The next step is to analyse macroscopically and microscopically the four- and eight-layer woven fabric specimens and try to understand the damage development on specimens with more than two woven layers. It is well known from the literature [e.g Tsoi 2003] that the best position to place the SMA wires is as far as possible from the impact surface. It would be interested to see, though, the results from impact testing specimens with more than two woven layers that have a layer of
wires in between each ply. This would also be a good way to increase the volume fraction of the SMA wires in these model specimens.

Finally, with regard to understanding the empirical relationship found between the energies involved during the impact event (U_{imp}, U_{abs} and U_{p}), the next step might be to try to model the impact events using a finite element analysis to establish whether the energy analysis emerging from the finite element model agrees with the experimental results.
References


References


- http://instron.com
- http://memory-metallic.de
References


• Stone, M. D J., “Controlled impact testing of composite laminates,” Final Year Project report, University of Surrey, UK (2007).


