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Smart textiles for the protection of armoured vehicles

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Abstract: The requirement for weight reduction encourages the use of composite materials which are lighter than steel for similar mechanical performance. In the field of vehicle armour, existing solutions can be improved by the introduction of new composite materials in combination with steel or ceramics. One of these solutions may lie in the use of three-dimensional (3D) textile structures, in particular a multi-layer fabric called 3D warp interlock, using different types of high performance fibres. A new textile composite solution is presented in this chapter. To enhance on-line measurement of mechanical stresses during impact, a fibrous sensor has been developed to better understand the *in-situ* behaviour of the target.

Key words: textile composite, yarn sensor, vehicle armouring, composite material.

11.1 Introduction

In all areas of transportation, strengthening of vehicles is required in order to protect some parts or the entire surface of the structure against impact. In the field of civil aerospace, satellites need to resist very high speed, small size meteorites. Commercial and other civilian aircraft need to be protected against bird strike and other atmospheric threats. Civilian vehicles such as car structures are designed to resist front and side crashes on static walls under certain speed limits, while high speed trains are subjected to animal and stone impacts to test their impact performance prior to commissioning. Finally, marine transport, such as high speed boats, have to cope with the impact of floating hazards such as wood or icebergs. For military applications, vehicles are designed to resist conventional ammunition with a range of mass and velocity, and also non-conventional projectiles contained in Improvised Explosive Devices (IEDs) (Wilson, 2005).

Two different approaches exist for vehicle armour. The most developed approach, which is called the 'up-armouring' of vehicles, consists of the application of existing solutions to provide impact protection to the structure surface. The less developed approach tends to integrate the protection material solutions inside the structure during the design phase. Traditional materials used for vehicle armour include steel, aluminium, titanium, depleted uranium (DU), and bullet-proof glass, ceramic and composite materials.

The Kyoto Protocol led the European platform ACARE (Advisory Council for Aeronautical Research in Europe), for example, to define ambitious strategic objectives (with respect to the effects on the environment) for air transport systems (ACARE, 2008). These goals include reduction by half of current average noise and CO_2 emission per passenger per kilometre. These goals, in turn, require weight reduction in aircraft. Similar targets for weight reduction are required in all areas of transportation whenever possible, keeping in view performance and economic constraints in order to optimise the consumption of energy. Energy consumption can be optimised by the replacement of steel parts by high performance composites. Moreover, the higher the speed of vehicles, the greater is the requirement for lighter material solutions.

Composite materials developed for aerospace, aeronautic, automotive, railway and marine applications are designed to be the best as regards technical performance and weight reduction, coupled with an appropriate price for the target market. Composite materials provide an attractive solution for up-armouring, as well as for the integrated armour of vehicles; in addition to mass reduction. Textile composites reinforced with aramid and polyethylene fibres are already used for up-armouring of vehicles. However, one of the weak points of these materials is their damage tolerance (shocks and delamination), which is associated with the difficulty of detecting damage, since impact damage is harder to see, unlike with steel. This lack of knowledge is compensated for by designing thicker, oversized parts, which contributes to undue weight gain. This design issue can be addressed by designing fibrous architectures having 3D reinforcement, which confer satisfactory mechanical properties in all directions.

Research is being carried out in order to better understand the failure mechanisms of armoured solution during ballistic impact. Improved understanding of different failure modes will lead to the development of better and more efficient armour. One of the possibilities in this regard is the integration of an intelligent sensor network in such a composite. This sensor network should be able to give real time, on-line information about deformation, and extent of damage and energy dissipation in the case of ballistic impact.

Some studies demonstrate that composites reinforced with 3D textile structures have high ballistic impact damage resistance and low velocity impact protection (Chou *et al*., 1992a; Miravete, 1999; Bahei-El-Din and Zikry, 2003). It has also been shown that 3D structural composites have better performance compared to two-dimensional (2D) laminates

(Baozhong *et al.*, 2005). According to impact studies carried out on 3D-woven composites (Chou *et al.*, 1992b; Baucom and Zikry, 2005; Khalid, 2006; Naik and Sekher, 2000), their high performance is mainly due to their greater resistance to delamination (Chou and Ko, 1989; Mouritz *et al.*, 1999). 3D angle warp interlock fabric offers higher strength and damage resistance as a consequence of their interlaced structure of warp and weft threads between the adjacent layers (Ko, 1989).

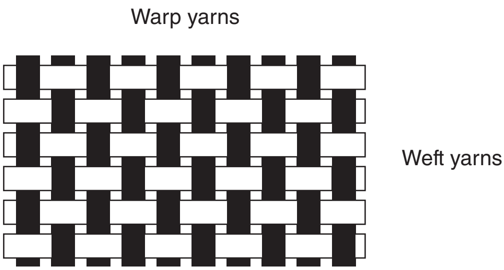
Low velocity impact properties of 3D woven composites are important for their various applications. This type of loading can occur when tools are dropped on the surface of a composite, or when the material is impacted by debris, fragments, or projectiles. In a recent study, two types of 3D woven basalt/aramid hybrid composites with similar fibre volume fractions and dimensions were tested. These were an inter-ply hybrid and an intra-ply composite. Post-mortem photographic analysis indicated that the inter-ply hybrid failed in layer-by-layer mode, leading to much larger energy absorption, while the intra-ply composite showed a brittle mode, resulting in significantly lower energy absorption (Wang *et al.*, 2008). It should also be mentioned here that 3D textile structural composites are much tougher between layers because many reinforcing yarns exist in the through-thickness direction. All of these research studies show the particular relevance of 3D composites for ballistic impact protection.

In order to show the efficacy of a 3D textile composite material, a special target has been designed using 3D woven composite material made with high performance fibres. The proposed solution is detailed in the sections giving the ballistic performance for given ammunition under testing conditions specified in the appropriate standard. At this stage of the authors' research, the *in-situ* performance of the protection during impact has not yet been evaluated. This will be possible only after the final development of adapted sensor yarns, whose technical characteristics are described later in this chapter.

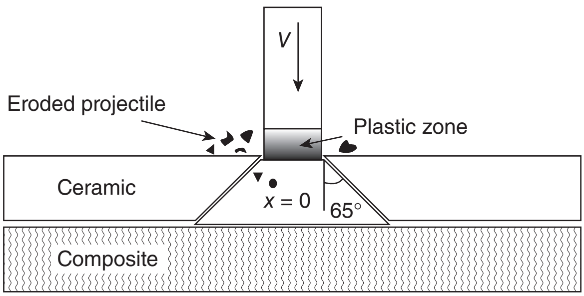
11.2 Understanding impact behaviour

The most used textile structures in technical applications are laminated, nonwoven, woven and knitted fabrics. Laminated or woven structures are mostly found in ballistic soft protection. In hard protection, a combination of textile composite materials and steel or ceramic plates is usually preferred. Such kinds of materials have to be efficient and resistant not only against impact but also against blast effects. Currently, 2D plain weave structures represent effective ballistic protection. They offer a low-cost method of producing large volumes of material, with similar mechanical resistance to that obtained with laminates of unidirectional tapes (Fig. 11.1).

Ceramics are used in ballistics to protect against the hardest of projectiles. The goal of ceramics is to deform the projectile in order to increase the



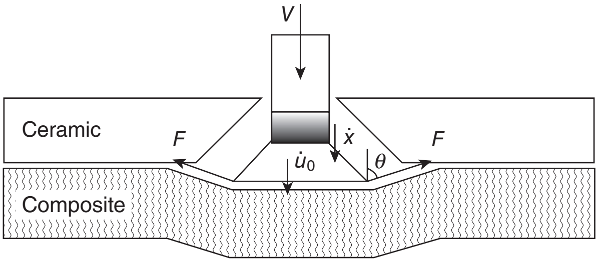
11.1 Plain weave fabric.



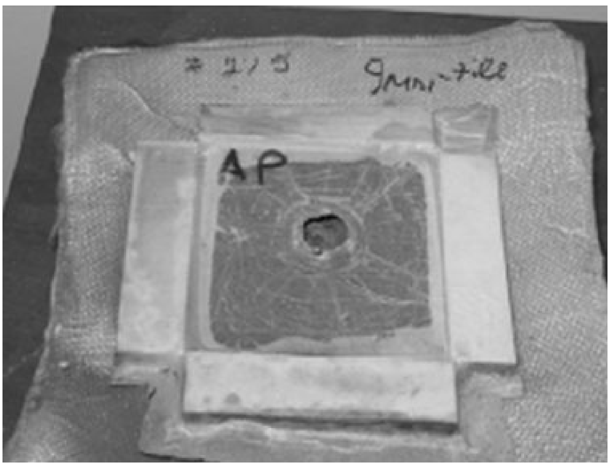
11.2 Configuration at the end of the first phase. *V*, impact velocity of the projectile; *x*, velocity of the plastic zone of the projectile equal to zero at the initial impact time, $t = 0$.

surface of the threat that is in contact with the material (Feli and Asgari, 2011). The optimum combination of ceramic/composite cannot be established: it depends on which kind of threat has to be stopped. Different ceramic composite constructions are recommended depending on the type of threat (Medvedovski, 2010).

When a projectile hits the target, the first phase is the destruction of the jacket surface: the ceramic is not penetrated. During this mechanism, a cone is formed through the ceramic (Fig. 11.2) due to the compressive wave formed, which is reflected as a tension wave. This tension wave induces cracking of the brittle ceramic. Then, during the second phase, the projectile penetrates (Fig. 11.3) and the whole structure becomes involved in slowing down the projectile. The fracture spreads all around the cone and the projectile is rubbed away. This erosion is induced by the difference between the velocity at the rear of the projectile and the head, which is the interface of the projectile with the ceramic. This difference causes a pressure on the projectile. During these two phases, the projectile loses some kinetic energy. The cone of deformation allows the spreading of the remaining energy over a larger area (Fig. 11.4). By doing so, the backing face of the composite may absorb the residual energy (Gonçalves *et al.*, 2004; Shokrieh and Javadpour, 2008).



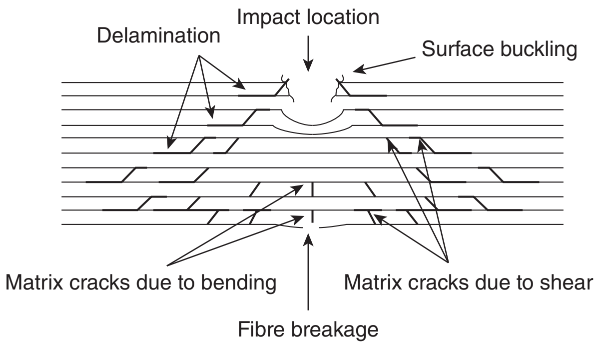
11.3 Phenomenological description of the second phase. *F*, resulted reactive force applied to the composite structure which causes the initiation of matrix cracks or intraply delamination; θ, angle of reactive force *F* with the projectile direction; $\dot{u}_0$, velocity of ceramic plug created at initial impact.



11.4 Ballistic test results for SiC-based ceramic (tile 100 × 100 mm) tested against threats. Caliber 7.62 × 63 mm Armour Piercing (type of rifle) M2 (length of rifle barrel, 10 in).

There is an important parameter that needs to be taken into account when ceramics are used as a strike face namely, the size of the tiles. Indeed, when a tile is impacted, it cracks due to the brittle behaviour of the ceramic. In the case of multiple impacts, if there is only one tile, the first shot will act as described previously, but the others will directly go through and the ceramic will not act efficiently. However, when armours are made with ceramic tiles, more than one tile is set up, in order to limit the propagation of the tile fracture.

In a composite structure, the absorption of energy depends on many parameters such as fibre material, matrix material, fibre/matrix interface, fibre orientation and structural geometry (Guoxing and Tongxi, 2003). As soon as the first layers are impacted, the whole composite structure is stressed (Fig. 11.5) and the energy transfer is governed mainly by the energy



11.5 Schematic representation showing a typical impact damage mode for a composite laminate.

absorption throughout the fibres (Shyr and Pan, 2003). Delamination is induced by the bending of each ply, which causes internal stress due to the difference in the value of the Poisson coefficient of yarns between the plies and the space between them. The effect of cracking along the matrix may be the cause of internal stress. Intra-ply delamination can be caused by the proliferation of matrix cracks (Johnson, 1985). This phenomenon is important in order to achieve energy absorption by ply-to-ply friction in the plane direction (Kang and Kim, 2000).

Taking into account time, three main stresses occur during a ballistic impact (Morye *et al*., 2000):

- the tensile failure of the first yarns,
- the elastic deformation of the structure,
- the intra-laminar ply delamination induced by the projectile.

The duration of each of these three main stresses is directly linked to the projectile velocity and also to the bullet type (shape, compounds, diameter and weight) (Carlucci and Jacobson, 2008).

The behaviour of the bullet varies during impact, depending on its velocity. At 'low' velocity (meaning under about 500 m/s for handgun threats), the bullet will be deformed in a 'mushroom' shape before being stopped. At medium velocity (between 500 and 1000 m/s for rifle ammunitions), the bullet explodes on impact. At very high velocity (above 1000 m/s: IEDs), the target structure acts like a fluid. During impact tests at speeds in excess of 300 m/s, a rigid behaviour of the structure is observed at the beginning of the penetration, causing a fracture in transverse shear of fibres, followed by flexural behaviour, creating multiple delaminations and breaks in tensioned fibres (Vasudev and Mehlman, 1987; Bless and Hartman, 1989; Dorey, 1989; Bannister *et al*., 1998).

The ballistic performance of a flat structure increases with the speed of the 'bending waves' and rupture time of the plies (Ayax, 1993). A simultaneous increase in these two parameters allows the material to absorb more energy from damage and deformation before the complete rupture of the flat structure. This implies the need to initiate and encourage an early propagation of delamination during the impact in the plate by careful choice of materials. One can, for example, use thick plies having low resistance, to create inter-laminar shear formed by resistant or ductile fibres.

The mechanism of delamination during impact has been the subject of many studies (Ross and Sierakowski, 1973; Cristescu *et al.*, 1975, Sierakowski, 1976). Most authors agree that delamination, along with fibre breakage, is the main mechanism of energy absorption. These mechanisms promote penetration resistance. The thickness of the target needs to be increased in order to improve penetration resistance. An increase in thickness implies an increase in mass per unit area of the composite material (Dorey, 1987; Savage, 1989).

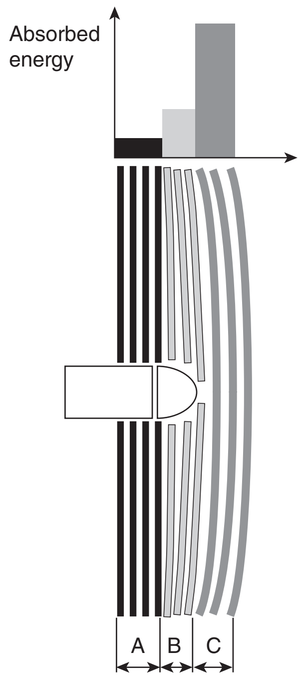
Materials made of ductile fibres (aramid, polyethylene) absorb more energy by deformation in axial compression and are more perforation resistant than materials reinforced with glass fibres (Bathnagar *et al.*, 1990; Hsieh *et al.*, 1990; Cunniff *et al.*, 1989). It can be assumed that there is a joint mechanism, which is governed by the bending rigidity of plies and properties of fibres (which break due to impact). This joint mechanism is responsible for the propagation of delamination and therefore energy absorption in the target plate.

In addition to the components' mechanical properties, the structure and thickness of the fabrics can influence the perforation resistance of a composite plate. In the case of a plate reinforced with aramid fabric, the penetration depth increases with increase of the speed. It therefore appears that the bending rigidity of plies, along with the ply thickness, is crucial to the overall ballistic performance of a plate.

The main energy absorption mechanisms involved in such interactions have been identified (Fig. 11.6). They are:

- transverse shear in broken fibres (Section A),
- tension in broken fibres (Section B),
- delamination (Section C).

There is a competition between the rupture mechanisms of fibres and delamination spread, both of which depend on projectile shape, the characteristics of fracture components and the bending rigidity of plies. Thus, to optimise the impact resistance, we must encourage the spread of delamination, in the sense that the plate has to absorb more energy from damage and deformation of the fibres before the complete failure of the material. Therefore it is necessary to decrease the inter-laminar shear resistance of the material, and increase joint stiffness and the bending plies' resistance to deformation or fibre rupture.

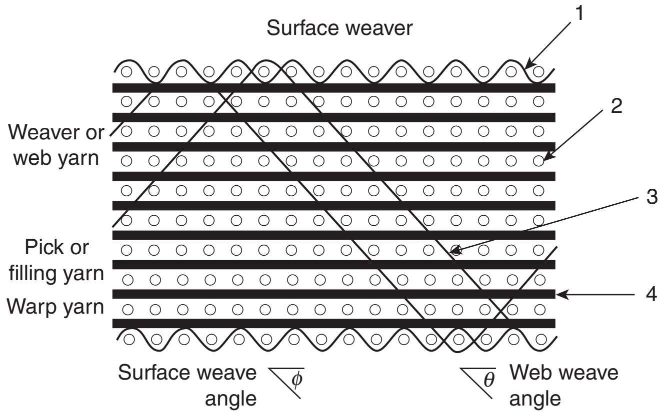


11.6 Explanation of delamination due to ballistic impact. A, transverse shear in broken fibres; B, tension in broken fibres; C, delamination.

The failure mode of orthogonal interlock fabric composites has been examined in detail (Boussu and Begus, 2008). The through-the-thickness yarns tend to increase the energy required to propagate an inter-laminar crack by the mechanism of fracture and pull-out of the z-axis fibres, and crack branching and deviating in the vicinity of z-axis fibres as well as in-plane fibres.

11.3 Bullet-proof textile composites for armoured vehicles

Conventional fabrics are sufficient as existing solutions but cannot help to reduce blunt trauma and weight in soft ballistic protection. On the other hand, for multi-layer fabrics stacked together for use inside an armour-plated solution for hard ballistic protection, low intra-laminar resistance is the main handicap. To cope with this lack of performance, different textile structures are being developed, especially 3D ones such as 3D warp interlock fabrics. Such structures are designed with reinforcement in the thickness direction. This helps in maintaining the cohesion of the structure during an impact and thus reduces the effects caused by intra-ply delamination. Owing to their improved damage tolerance (confining the term to damage



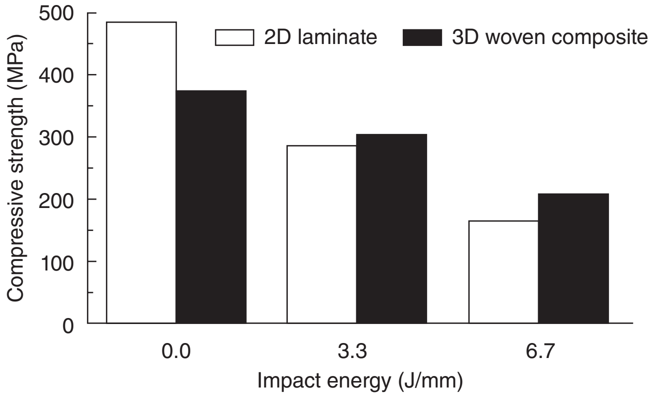
11.7 Schematic representation of warp interlock structure. ϕ, Crimp angle of surface warp yarns (surface weave angle); θ, crimp angle of warp yarns which bind the layers (web weave yarns).

during ballistic impact), warp interlock structures are expected to be more efficient in the case of multiple impacts.

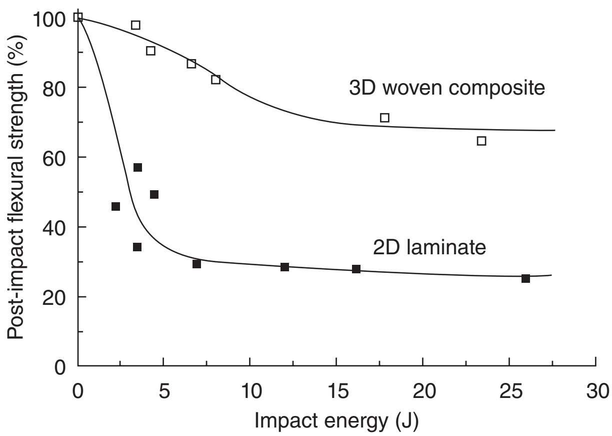
11.3.1 3D-warp interlock fabric as a solution

Figure 11.7 illustrates a 3D warp interlock fabric made of different yarns in the three directions (Hu, 2008). The first yarn (Number 1) called the 'surface weaver', is used when the structure needs a smooth surface and ensures the consolidation of the 3D woven structure from the top to bottom. The second yarn (Number 2) is called the 'fill yarn or weft yarn', and gives the mechanical properties in the transverse direction. The third yarn (Number 3), called the 'warp yarn', is also used for mechanical properties and undergoes undulations because it works in the fabric thickness direction. The fourth yarn (Number 4), called the 'longitudinal yarn' or 'warp yarn', gives resistance and toughness in the longitudinal direction.

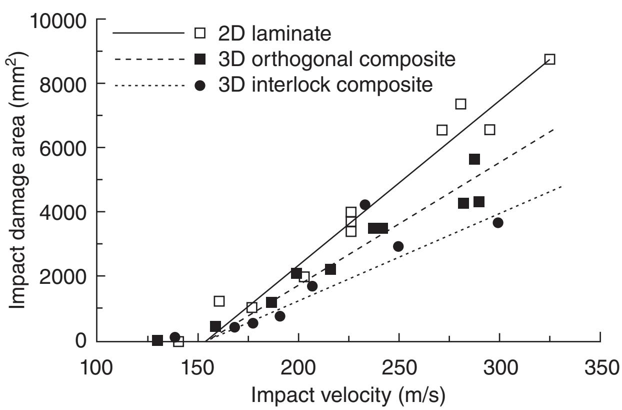
Tong *et al*. (2002) have mentioned that 3D structures show an increase in compression (Fig. 11.8) and flexural (Fig. 11.9) strength, as well as a decrease in the delaminated area (Fig. 11.10) after impact compared with 2D laminates. Moreover, shorter interlacing yarns in some architectures allow fabrics to bend easily and to shear more effectively, unlike with 2D laminates. The main disadvantages encountered with ballistic structures include the adverse effects of crossover points in fabrics and laminate delamination (Dadkhah *et al*., 1995; Chiu *et al*., 2004). This is a significant factor in the case of multiple-impacts because the integrity of the structure is adversely affected. Integrating diverse technologies, including 3D textile fabrics, in order to take advantage of their strong points seems to be the most interesting solution.



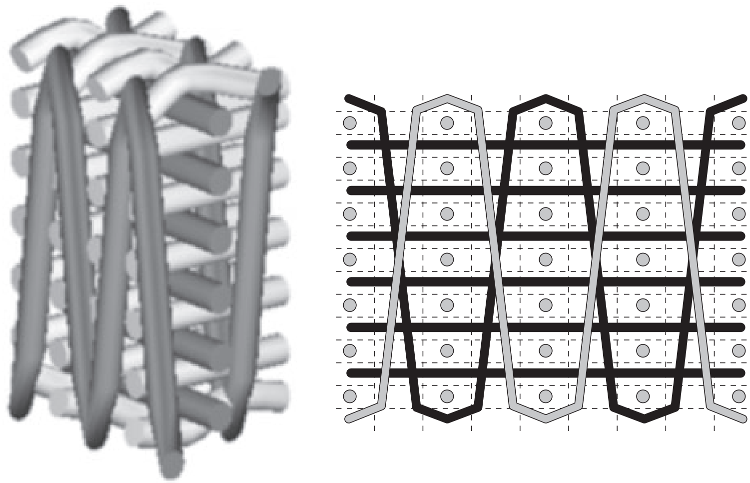
11.8 Effect of weaving on compressive behaviour.



11.9 Effect of weaving on flexural strength.



11.10 Effect of weaving on impact damage area.



11.11 Illustration of an orthogonal warp interlock woven fabric (seven layers). (a) 3D view, (b) warp yarn evolution.

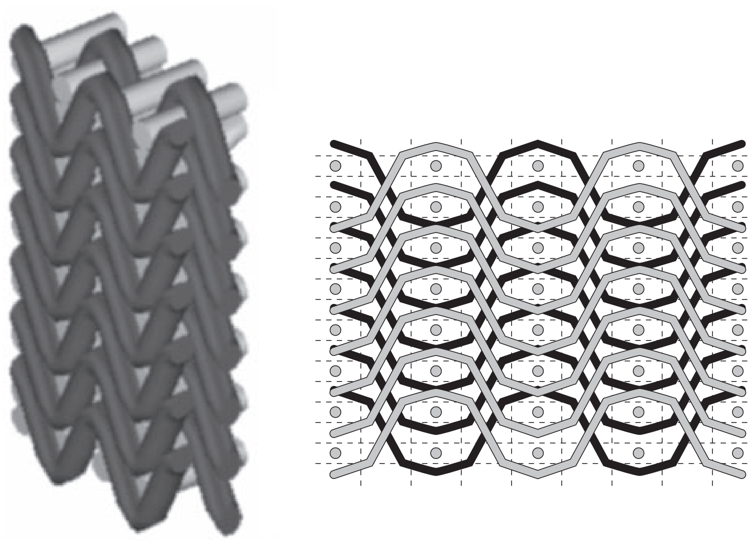
Different types of 3D woven architectures can be chosen. The choice allows one to design composite material having suitable tensile strength, shear strength and delamination properties according to the expected nature of the ballistic impact (Tsai *et al*., 2000; Sun *et al*., 2005, 2009). Three types of multilayer woven architectures, namely layer-to-layer, orthogonal and through-the-thickness interlocks, can be designed within the framework of warp interlocks.

In the orthogonal warp interlock fabrics (Fig. 11.11) (Wisetex® Software), the z-yarns go through the entire thickness of the fabric between only two columns of weft yarns. The main advantage is the presence of the column of longitudinal yarns, which improves the mechanical properties of the fabric and limits the crimp inside the structure. Conversely, the two yarns that go through the thickness induce a weakness zone.

In the layer-to-layer interlock fabrics (Fig. 11.12), the z-yarns connect individual layers of the fabric. This type of architecture allows control of crimp. Indeed there are many configurations and quantities of z-yarns that can be selected in order to assemble the layers together.

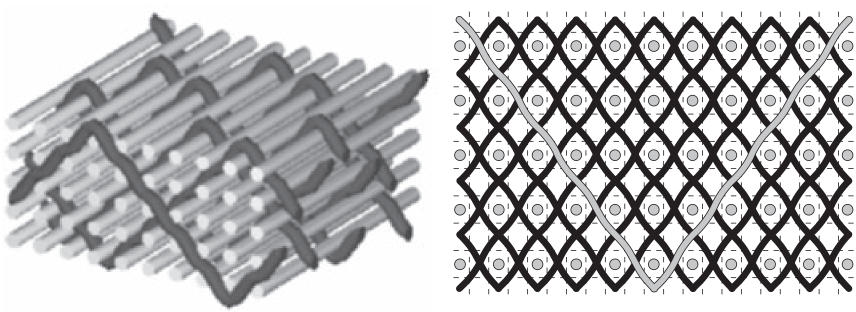
In through-the-thickness interlocks (Fig. 11.13), the z-yarns traverse the entire thickness of the fabric across more than two columns of weft yarns. This configuration induces greater thickness than other types. It is possible to introduce a longitudinal yarn inside the structure in order to compensate for the loss of mechanical properties.

In view of the advantages represented by warp interlock fabrics, one of the proposed solutions to improve the ballistic protection for vehicle armour



(a) (b)

11.12 Illustration of a layer-to-layer interlock woven fabric (eight layers). (a) 3D view, (b) warp yarn evolution.



(a) (b)

11.13 Illustration of a through the thickness interlock woven fabric (five layers). (a) 3D view, (b) warp yarn evolution.

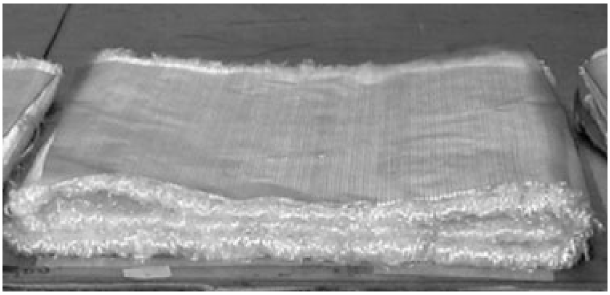
and reduce the weight is to integrate 3D fibrous architectures at different specific locations, allowing the absorption of an estimated amount of energy.

11.3.2 Design of a new armour-plated protection system

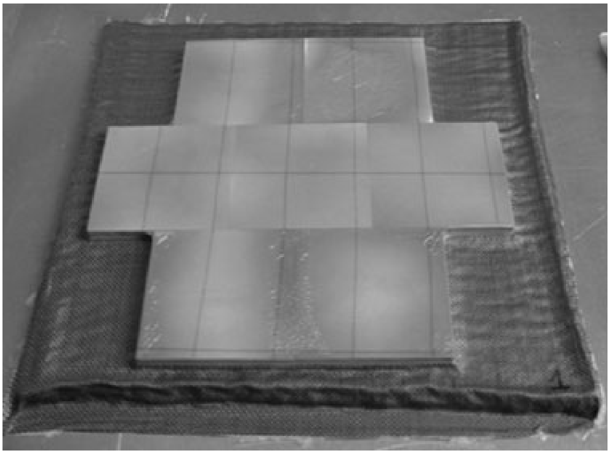
The particular advantage of ceramic backed by composite armour lies in its high hardness and relatively low density as compared with steel plates (for similar energy absorption) (Boussu and Begus, 2008). As soon as an armour-piercing bullet impacts the hard armour, the ceramic strike face deforms and breaks up the bullet, thereby greatly decreasing the impact energy. Then, the backing, located behind the ceramic plate, absorbs the energy by deforming the fibrous structure and thus stops the fragments.

The ceramic facing-element can be a continuous monolithic plate or a plurality of individual square ceramic tiles or otherwise, and can be shaped to suit the dimensional needs of a particular application. The most used ceramic types are alumina Al_2O_3 (ρ = 3.9 g/cm^3), silicon carbide SiC (ρ = 3.2 g/cm^3) and boron carbide B_4C (ρ = 2.52 g/cm^3). Different layers of the textile structure are stacked together to achieve the final backing of the target (Fig. 11.14). Ceramic tiles or alumina ones are placed in front of the textile structure to be moulded and pressed during the composite manufacturing process (Fig. 11.15).

Three targets have been tested with 12.7 mm calibre armour piercing ammunition of 43 g weight, which corresponds to a total energy of around



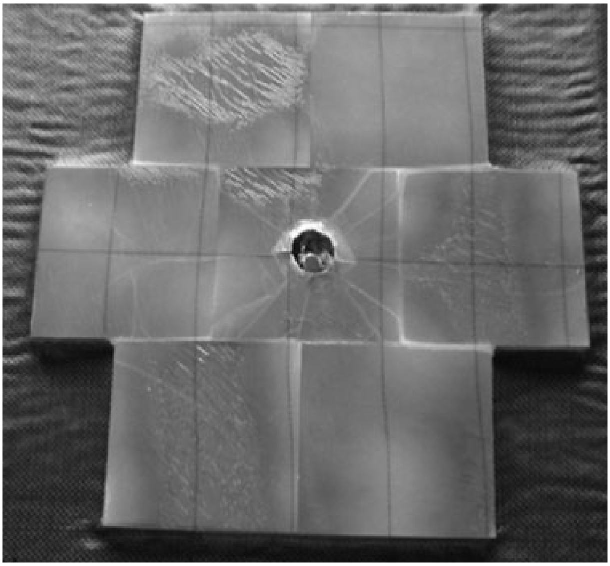
11.14 Stacking of three layers of angle interlock fabric.



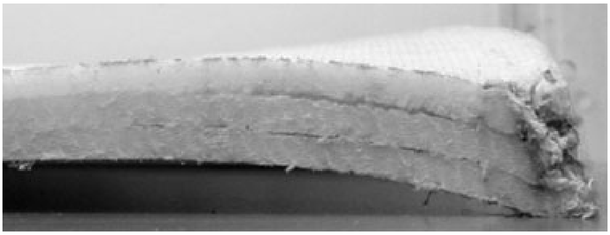
11.15 Final view of the target.

8000 J to be absorbed. Only one bullet was fired, at the centre of each target with a speed of 610 m/s, in accordance with the MIL-PRF-46103-E standard (for use in the field of aeronautics only). None of the targets failed during impact tests. For one of the targets, the impact hole had a diameter of 25 mm. After the first impact (Fig. 11.16), most of the ceramic tiles were still 'glued' to the backing, which may have led to better propagation of kinetic energy to the textile backing.

Post mortem analysis (Fig. 11.17) of the 3D woven textile composite removed from the target allowed a better understanding of its ballistic performance. It was revealed that intra-ply delamination between the three 3D warp interlock fabrics leads to better energy absorption during the impact of deformed hard core ammunition. This target made with warp angle interlock fabric was compared with existing unidirectional laminates.



11.16 Impacted target with 12.7 mm cartridge.



11.17 Lateral view of the 3D textile composite of the final target.

It was found that the same bullet-stopping result is achieved for both the targets, but the cost of production for warp angle interlock fabric is reduced by half, along with a 10% weight reduction. This is primarily due to the good delamination resistance of the 3D woven fabric and one-step production made possible by the 3D interlock weaving process.

In conclusion, a 3D warp interlock fabric used as the reinforcing fibrous material inside a textile composite stacked with ceramic tiles allows reduction of mass, with the same ballistic protection for vehicle armouring. The predicted behaviour of these three warp interlock fabrics during the impact corresponded well with their actual behaviour. In order to improve the performance of this protection under identical firing conditions, a localised measurement of energy dissipation inside the warp interlock fabric would help to better understand the mechanical stresses and their spread under dynamic conditions. Thus, the other part of our research is related to the development of sensor yarns for real time *in-situ* measurement of stresses acting on the target during an impact. The mechanical properties of yarns vary greatly during an impact, depending on the impact velocity. That is why, initially, our research focused mainly on real time, *in-situ* monitoring of quasi-static tensile loading using flexible textile sensors.

11.4 Using sensor networks in composites to measure impact behaviour and material performance *in situ*

Good quality and reliability are basic requirements for advanced composite structures, which are often used under harsh conditions. To improve their performance, monitoring during the curing process is clearly necessary. At the same time, in service, non-destructive evaluation (NDE) is needed to keep these structures operating safely and reliably. NDE techniques have been developed in the past, including ultrasonic scanning, acoustic emission (AE), shearography, stimulated infrared thermography (SIT), Fibre Bragg Grating (FBG) sensing and vibration testing (Black, 2008).

The challenge today is to develop new, low-cost techniques that can perform online structural health assessment, starting from the manufacture of composite structure to the actual service of these structures in the field. Moreover, NDE techniques have to be integrated in the design phase, and sensors should be inserted during the fabrication of composites in order to improve accuracy and reduce costs. The classical NDE techniques are difficult to adapt. They are not well suited for on-line structural health monitoring because of difficulties in making *in-situ* implementation. Moreover, it is important to understand the stress–strain conditions during damage. A record of stress–strain history prior to damage also helps in understanding the cause of irreversible damage (Wang and Chung, 2006).

One possible solution is to use intelligent textile materials and structures that provide a real possibility for on line and *in-situ* monitoring of structural integrity. These materials not only perform the traditional functions of a structural material, but also have actuating, sensing and microprocessing capabilities. Such intelligent materials are made by coating or treating textile yarns, filaments or fabrics with nanoparticles or conductive and semi-conductive polymers, giving them special properties (Scilingo *et al*., 2003; Dharap *et al*., 2004; Fiedler *et al*., 2004; Lorussi *et al*., 2005; Huang *et al*., 2008a, b).

A review of piezoresistive sensing approaches already being applied to measure strain in fabrics/composites shows that several sensing mechanisms exist. These approaches may be categorised, on the basis of manufacturing technology, as follows.

- Nanotube networks (Zhang *et al*., 2006; Schueler *et al*., 2001; Fiedler *et al*., 2004; Peng *et al*., 2001).
- Carbon tows for self-sensing (Wang and Chung, 2006).
- Semi conductive coatings (Dharap *et al*., 2004; Cochrane *et al*., 2007; Peng *et al*., 2001).

None of these have gained universal acceptance, either as standards in structural health monitoring of composites or for the fabrication of intelligent textiles.

Nanotubes have been investigated in detail for use as sensing mechanisms, both for smart textile applications and for structural-health monitoring of composites. Significant challenges still exist in their development; for example, the efficient growth of macroscopic-length carbon nanotubes, controlled growth of nanotubes on desired substrates, durability of nanotube-based sensors and actuators, and effective dispersion in polymer matrices and their orientation. Therefore, there is a need to develop both experimental and analytical techniques to bridge the nano and macro scales towards optimization, so as to use nanotube networks as sensors inside macro-scale (fabric) or meso-scale (tow) composites (Lorussi *et al.*, 2004).

Carbon-fibre reinforced composites offer a unique possibility of using carbon tows as a sensing network because of their conductivity. However such an approach can only be used for conductive fibre based composites. Moreover, before applying such an approach for structural health monitoring it is imperative to understand the deformation mechanism of the reinforcement. Any anomaly in the deformation mechanism can threaten the sensing mechanism's validity and efficacy.

Semi-conductive coatings, such as silicon flexible skins, have been used for intelligent textiles (Katragadda and Xu, 2008), e.g. as flexible fibrous transistors (Fiedler *et al*., 2004; Lee and Subramanian, 2005) on textile fibres, to detect the physiological condition of the wearer (Huang *et al*., 2008a, b;

Scilingo *et al*., 2003; Cochrane *et al*., 2007). Such coatings on fabrics, yarns or fibres are easy to realise and can be made wash resistant. Their use as electrical percolation networks for sensing in structural-health monitoring applications is quite promising and needs to be further investigated. Electrical percolation is a phenomenon defining the transition from an electrically non-conductive to an electrically conductive state of the sensor. Conductive paths constituted of conductive particles (charges) contributing to percolation appear when the strain gauge length decreases (global sensor resistance decreases) and disappear when its length increases (global sensor resistance increases). Therefore, the global sensor resistance used to measure the elongation of the sensor depends on the number of electrically conductive paths. This type of sensor is also called a piezoresistive sensor.

New piezoresistive textile sensors based on semi-conductive coatings has been designed, developed and optimised by GEMTEX Laboratory (France). They are suitable for use in composite structural parts reinforced with 3D preforms and have been specially designed to offer the following advantages.

- They can be embedded inside the reinforcement during weaving.
- They have all the characteristics of a traditional textile material (light weight and flexibility, and thus the capability to adopt the geometry of the reinforcement and become an integral part of it).
- Since these sensors are inserted during the weaving process, they are subjected to similar strains as the composite itself. Measurement of resistance change with variation in the sensor's length is a way of determining, *in-situ*, strains in the composite material that lead to its final damage.
- The fibrous sensors are not supposed to modify the overall structural and mechanical properties of the composite as they are integrated locally and the bulk of the structure is composed of high-performance multifilament tows.
- Embedding such an intelligent piezoresistive sensor inside the reinforcement during the weaving process is the most convenient and cost-effective way of inserting a sensor for structural health monitoring (SHM).

Development and optimisation of such piezoresistive sensors has been carried out in order to render them sensitive enough to measure *in-situ* strains inside the composite part. Sensitivity is important as the targeted application usually undergoes very low strains, but even such low strains and/or vibrations during the life-time of composite parts are critical. Often they are used in areas where structural integrity cannot be compromised (aircraft wings, bodies, etc.). Optimisation of sensors is followed by their insertion in the reinforcement, during the weaving process, on a special loom modified and adapted for multilayer warp interlock weaving. The reinforcement is then impregnated with epoxy resin, using an infusion process, to form a stiff composite material.

In the first place, only tensile loading was considered in order to validate the concept of *in situ* measurement with the sensor, compatible with the manufacturing method of carbon composites. Afterwards, fatigue and impact monitoring using the same kind of sensors will be realised. The fatigue properties may also be estimated from the history recorded during the target's life time using our fibrous sensor.

Since the carbon multifilament tows are conductive and may disturb the functioning of the piezoresistive fibrous sensor, it is imperative to coat the sensor with an additional insulating layer. The compatibility of the interfacial properties of the insulating layer with the carbon nanoparticles coated on the sensory yarn surface on one side and with the epoxy resin on the other side is very important. An insulating medium that has good adhesion to the coated yarn, as well as with the resin, should be used.

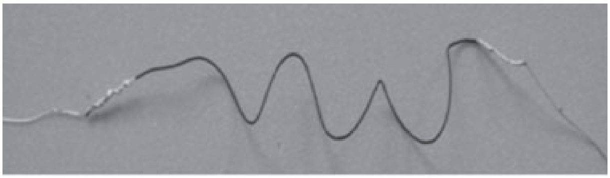
11.4.1 Sensor design

Several different coating techniques for intelligent textile structures exist. The one described here was developed by Cochrane *et al*. Yarns and filaments were coated with the conductive layer using dispersed carbon black particles (Printex® L6) in polymer (Evoprene® 007) solution, utilising chloroform as a solvent and dispersing medium. In order to characterise the sensitivity and adherence of the coating on different substrates, a solution having 35% carbon black concentration was coated onto various yarns and filaments (polyester, polyamide, polyethylene and cotton). It was found that polyethylene was the best substrate as far as resistivity and uniformity of the conductive layer was concerned. The coatings on polyethylene were easy to achieve due to good substrate–conductive solution interfacial properties. Coatings on polyethylene were reproducible and gave coherent results. Therefore two-ply polyethylene filament was chosen for sensor development.

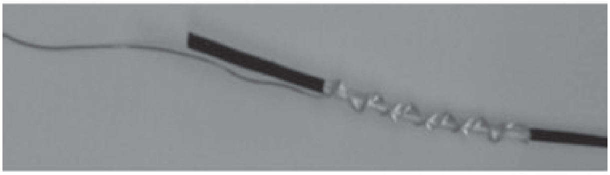
The fundamental principle of functioning of this fibrous strain gauge is based on forming (and deforming) the electrical conductive paths (percolation networks) in a coated layer made of conductive nano charges with gauge deformations. Sensor structural and geometrical parameters, along with initial electrical resistance, are shown in Table 11.1. The two ends of the coated polyethylene filaments were additionally coated with silver paint, and fine copper wire was attached to the two ends with the help of this paint (as shown in the Fig. 11.18). In this way, secure connections were realised, enabling the reduction of the contact resistance to a minimum. Transversal and longitudinal sections of the sensor, obtained through SEM

Table 11.1 Sensor properties

Parameter	Value
Linear density of the filament	48.23 g/km
Diameter of the filament	0.70 mm
Average width of the sensor	1.68 mm
Average thickness of the sensor	1.26 mm
Aspect ratio of the sensor	1.33
Initial resistance of the sensor	43.30 kΩ



(a)



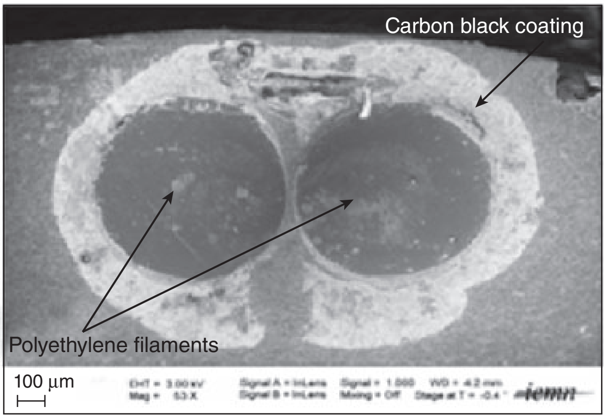
(b)

11.18 Textile sensor before its integration in woven fabric. (a) Carbon black-coated sensor with polyethylene double-ply substrate, (b) detail of connections at the ends.

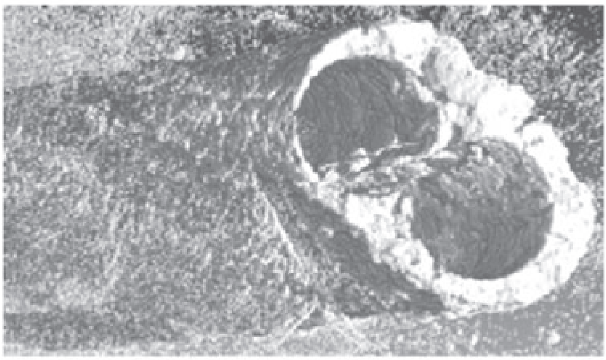
and tomography, are shown in Fig. 11.19a and 11.19b, respectively. For insertion in conductive, fibre-based reinforcements, such as that woven using carbon multifilament tows, the sensor was coated with Latex Abformmasse supplied by VossChemie®, so as to insulate the sensor from the surrounding carbon tows.

11.4.2 Reinforcement architecture and sensor insertion

An orthogonal/layer-to-layer interlock structure with 13 layers was woven on a modified conventional loom. 200-tex multifilament carbon tows (6K), supplied by Hercules Inc., were used in the warp and weft. The reinforcement and composite parameters are listed in Table 11.2. Sensors can be inserted in warp or weft directions during weaving. Given the technical complications associated with sensor insertion in the warp direction during weaving on a loom, insertion in the weft direction has been carried out for



(a)

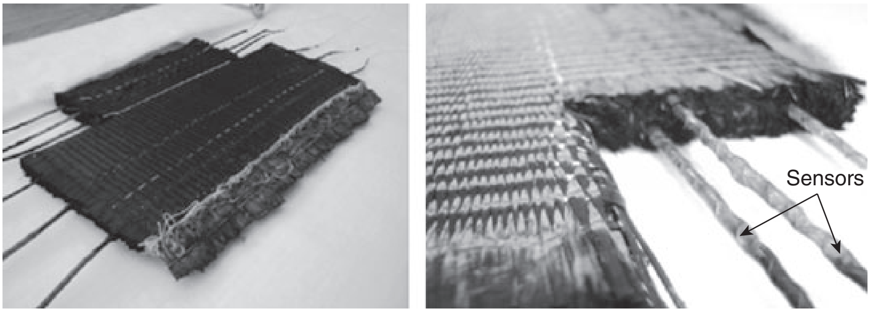


(b)

11.19 Images of the sensor obtained through SEM and tomography. (a) Transversal section (SEM), (b) longitudinal view (tomography).

Table 11.2 Reinforcement and composite specifications

Parameter	Value
Linear density of warp tow	200 g/km
Linear density of weft tow	200 g/km
Average thickness of reinforcement	6.5 mm
Warp tows density	24 tows/cm
Weft tows density	169 tows/cm
Areal weight	3908 g/m^2
Fibre volume fraction	34.16%



(a) (b)

11.20 Reinforcement with protruding sensor connections.

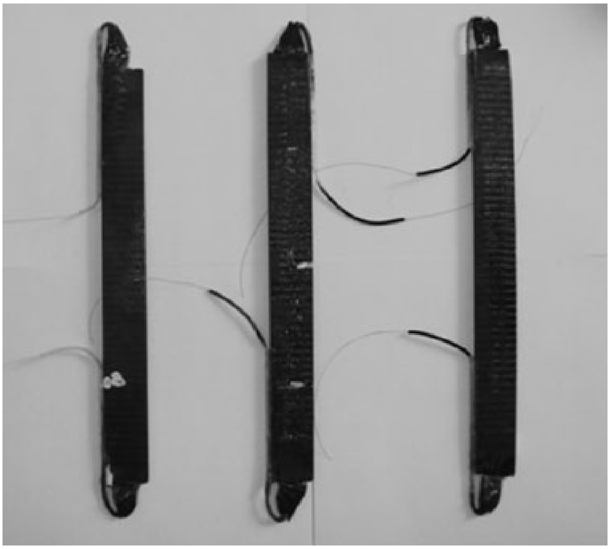
preliminary studies. The location of the sensor in the reinforcement was chosen to be in the middle of the structure. Moreover, since the sensor is inserted during the weaving process, it follows the same trajectory as the carbon tows inside the reinforcement. Figure 11.20 is a photograph of the off-the-loom dry reinforcement. Latex-coated sensor connections can be seen protruding from the reinforcement.

11.4.3 Composite manufacturing process

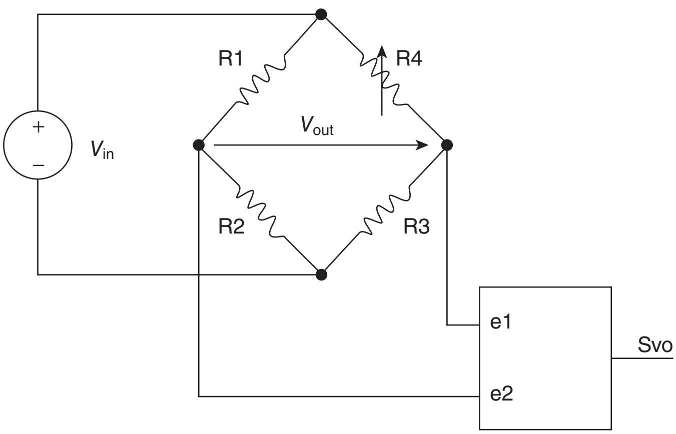
After weaving, the reinforcement was carefully removed from the loom and was impregnated using a vacuum bag infusion process in order to make the composite part stiff. The resin employed was epoxy Epolam 5015. The two connections of the sensor that remained outside the reinforcement at the two ends were carefully separated from the rest of the mould. This was done by creating two vacuum sub-moulds inside the larger mould so that the resin could not impregnate the two connections of the sensor. The impregnated composite samples were cut into slabs of 25 cm × 2.5 cm (Fig. 11.21).

11.4.4 Preliminary sensor measurements (before insertion in composite)

The sensor was tested in traction on an MTS ½ tester (MTS, Material Testing System). The sensor underwent quasi-static tensile loading at a constant test speed of 5 mm/min. A Keithley® KUSB-3100 data acquisition module was employed for the purpose of determining voltage variation during data acquisition. A Wheatstone Bridge (Fig. 11.22) was used to measure the unknown variable resistance of the sensor as a function of output voltage. The data acquisition module, when connected to a computer, showed the voltage variation data in real time via the software interface (Keithley QuickDAQ). The data could be saved on a hard disk for further



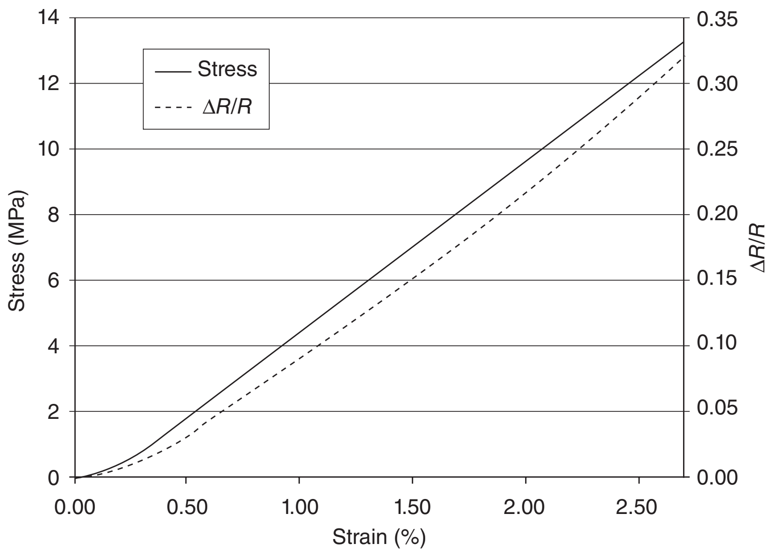
11.21 Composite structural part with textile sensor for tensile test.



11.22 Wheatstone bridge configuration used for differential voltage variation measurement caused by resistance variation in the sensor R4 (strain gage). R1, R2, R3 are resistors; V_{in}, input or excitation voltage; V_{out}, output voltage; e1 and e2, analog to digital converter input; Svo, signal to computer.

treatment in any suitable format. Noise reduction in the resistance variation data was achieved using a low pass filter.

The resultant stress–strain–resistance relationship curve, up to 2.5% elongation of the out of composite sensor (before insertion in the reinforcement), is shown in Fig. 11.23. It may be noticed that the stress *vs*. strain curve has the same shape as the normalized resistance ($\Delta R/R$) *vs*. strain



11.23 Normalised resistance, and stress against strain for sensor outside composite.

curve. This validates the electromechanical properties of the fibrous sensor for strains ranging from 0 to 2.5%.

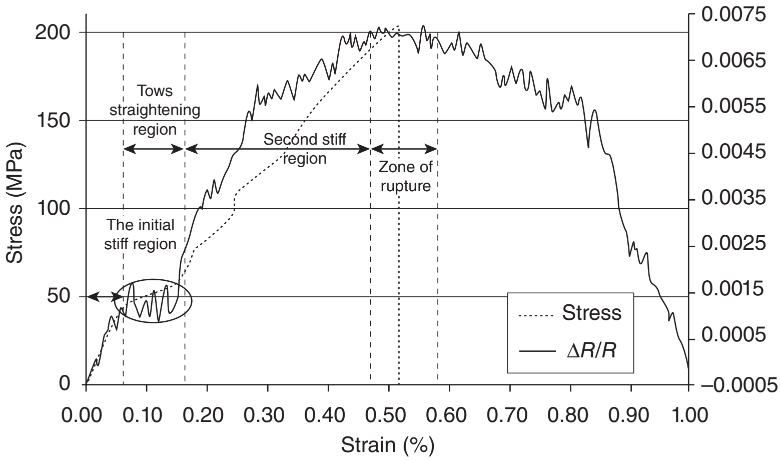
11.4.5 On-line sensor measurements (after insertion in composite)

The composite specimens were tested on an Instron© 8500 tester (Fig. 11.24). Tensile strength tests were performed on the composite specimens according to the standard NF EN ISO 527–4, 1992, in the weft direction, i.e. the direction parallel to the inserted sensor. The same Wheatstone bridge was used for resistance variation measurement and the configuration of the testing equipment was also kept the same. The composite structural part was tested at a constant test speed of 5 mm/min. The composite underwent traction until rupture.

The resultant stress–strain–resistance relationship curve is shown in Fig. 11.25. It can be seen that the normalised resistance follows the stress–strain curve. The stress–strain–resistance curve can be divided into four regions, namely: the initial stiff region where the composite exhibits toughness against the applied load represented by a high slope, a second region called the 'tows straightening region'. It is followed by another stiff region, and finally the zone of rupture. The rupture occurred at the strain of 0.52%, after which the tensile strength tester came back to its initial position at the same speed (5 mm/min.). Since the fibrous sensor had not been broken,

(a) (b)

11.24 Instron 8500 tensile strength tester.



11.25 Normalised resistance and stress against strain for sensor inside composite.

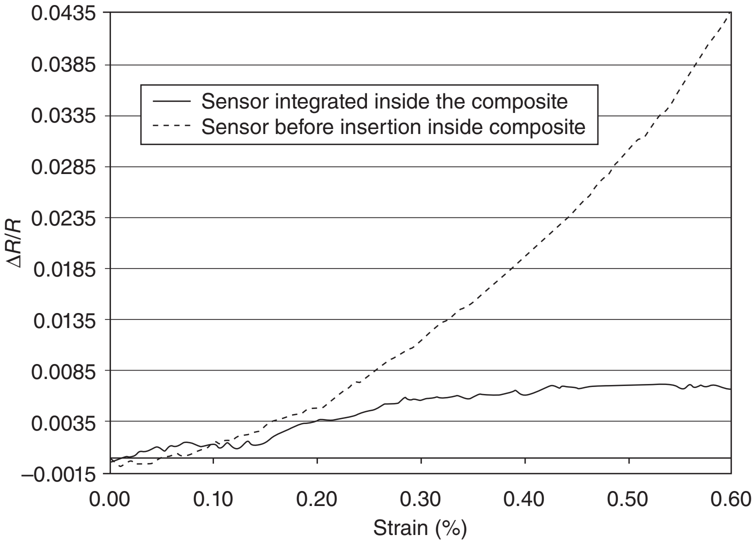
ΔR/R decreased until zero as the tester returned to its initial position. However this decrease was not linear because the sensor was still intact while the resin–sensor interface was partially damaged, causing its non-linear behaviour.

A composite micrograph in the weft direction revealed that the weft tows were highly crimped. In the initial stiff region, micro-cracks start appearing as the composite specimen undergoes traction, but the interface between resin and multifilament tows is still intact. That is why the composite exhibits rigid behaviour. In Fig. 11.25 it can be observed that, after the initial stiff region, the highly crimped tows tend to straighten due to increasing tensile load in the second region. In this region, the micro-cracks give way to relative slippage of the highly crimped tows in the matrix, i.e. the resin–tow interface is relatively weakened. This region, called the tow straightening region, is enclosed in an ellipse in Fig. 11.25. The region is characterised by high Poisson contraction. It can also be remarked that the sensor resistance follows the stress–strain curve, but in the second region, the electrical resistance curve is noisier as compared to other regions of the curve, which might signify slippage of the tows, as well as the sensor, in their sockets.

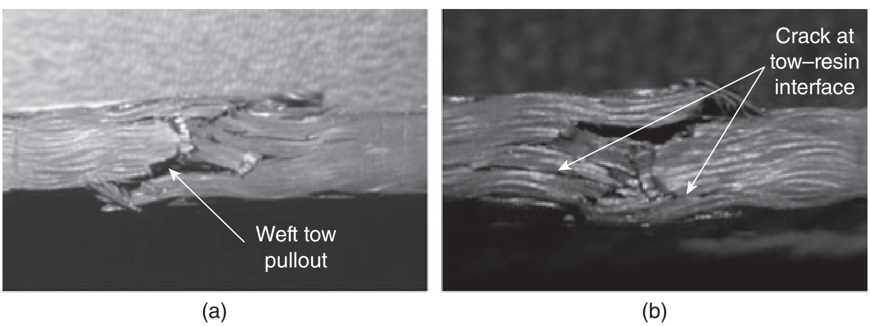
This second region is followed by the third region called the ‘second stiff region’ where the tows are locked in their sockets. In this region the tows resist the applied load and exhibit stiff behaviour as they regain some of their initial stiffness after the straightening of tows in the second region. The electrical resistance varies almost linearly with the applied load in this region. The third region is followed by the zone of rupture of the composite, in which the electrical resistance, having attained the highest value, starts dropping down. The normalised resistance starts dropping after the rupture. The fact that the sensor resistance attains its initial value after the rupture signifies that the sensor, owing to its elastic properties, is not destroyed with the composite.

In Fig. 11.26, a comparison of the electrical resistance variation of identical out-of-composite and *in-situ* sensors is given. Initially, the sensors behave essentially in the same way, as is obvious from the two curves. The two curves part ways at around 0.20% elongation, which roughly coincides with the beginning of the third region, namely the second stiff region in Fig. 11.25. Unlike the *in-situ* sensor, the out-of-composite sensor has linear resistance–strain relationship. This difference in the two curves signifies the differences in the region around the two sensors. The out-of-composite sensor is unconstrained while the *in-situ* sensor is constrained by the reinforcement and resin inside the composite as it has to follow the deformation pattern of the composite.

In Fig. 11.27, photographs of specimens that have undergone these tensile tests are shown. The mode of rupture for all the samples was nearly the same. There was a single zone of rupture half way along the length of samples where tows give in to applied traction in rather a brittle fashion. Tow pull out could also be seen in some of the samples but did not seem to be the dominant mode of rupture (Fig. 11.27a). Low strain to failure was due to low fibre pullout during failure. The initial crack seems to have rendered the structure weak. The crack then propagated in the structure until the complete fracture of tows at the zone of rupture (Fig. 11.27b).

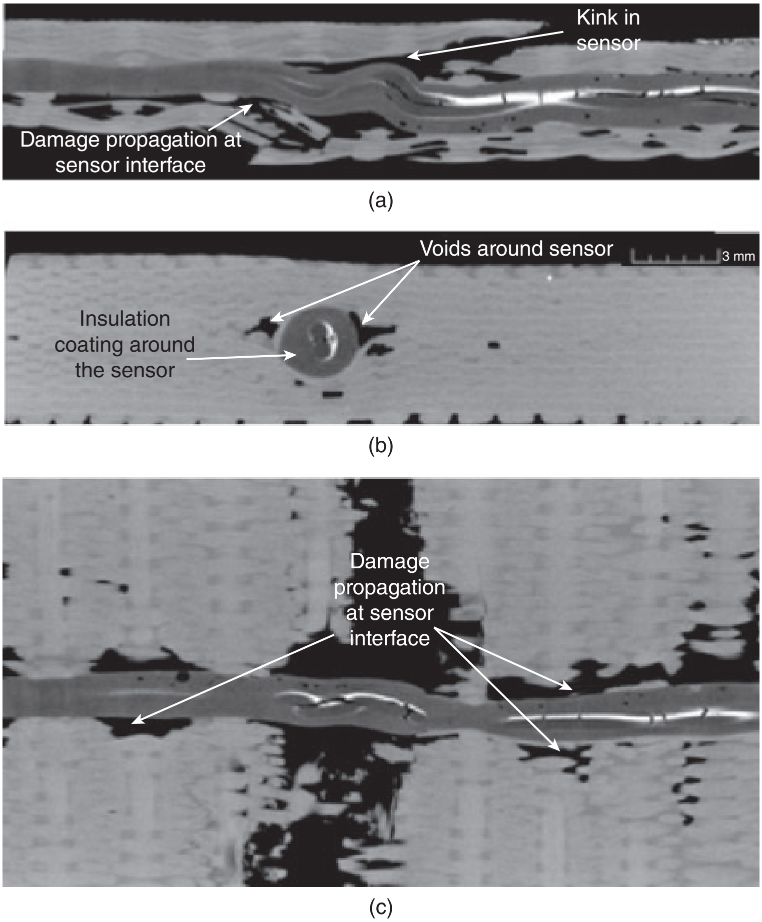


11.26 Normalised resistance against strain for integrated and out-of-composite sensors.



11.27 Surface photographs of composite samples taken after tensile strength tests. (a) Warp tow pullout, (b) crack at tow–resin interface.

Figure 11.28 shows tomographical images of the samples that underwent traction. The sensor cross-section and its path at and near the zone of rupture can be observed. In Fig. 11.28(a, b, c), it can be observed that the sensor–resin interface had many voids. These were caused by poor resin–sensor interfacial properties. The insulating medium on the sensor surface needs to have good adherence with the epoxy resin and carbon fibre reinforcements. Damage that occurred at the main rupture zone had propagated along the sensor boundary, giving rise to debonding of the sensor. A kink in the sensor can be observed (Fig. 11.28a) which was caused by the relaxation of the sensor as it tried to regain its original dimensions after the



11.28 Tomographical images of sensor inside a tested sample near the zone of rupture. (a) Longitudinal section, (b) transversal section, (c) top view.

tensile loading damaged the composite sample. The insulation coating around the sensor rendered it thick, which is undesirable for high-performance composite materials because thick insulation coatings might adversely affect the mechanical properties.

In conclusion, the sensor developed for *in-situ* measurements on carbon fibre composite structures is capable of detecting strain in the structure. The electrical resistance variation in the sensor follows the deformation pattern of the composite, mainly due to its sensitivity to its environment and because of the fact that it is integrated in the structure and follows the fibre architecture of the reinforcement. It has been shown that integrated textile sensors inside the reinforcement can be used as *in-situ* strain gauges for composite materials. Moreover, if the placement of these sensors inside the reinforcement is carefully chosen, they can be used to follow the local deformation pattern so as to better understand the deformation mechanisms and predict the life-time of the composite parts. At present, the sensors have been tested for tensile loading. Tensile strength tests were chosen to demonstrate the basic features of this novel SHM approach. In the future, these sensors will be used for bending and fatigue tests on similar 3D carbon fibre woven reinforcement-based composites.

However, optimisation of sensors needs to be carried out in order to prepare thinner sensors having negligible effect on reinforcement geometrical and mechanical properties. For carbon fibre based reinforcements, which require an insulation coating on the sensor surface, a better and finer coating needs to be applied. In view of the test results presented, it can be concluded that these sensors can be used for *in-situ* health monitoring of various types of composites under quasi-static mechanical stress, especially for different deformation modes of 3D or multilayer reinforcements in which different layers do not necessarily deform in a homogenous manner. For instance, the fibrous sensors may well be used for the detection of transverse strains and for the detection of interlaminar slippage.

Currently, research work is being carried out in our laboratory to develop sensor yarns suitable for detecting dynamic loads and ballistic impacts. The main challenge lies in the development of a highly sensitive sensor, and a data acquisition and treatment module capable of detecting high-speed ballistic impacts properly and accurately. It is expected that such intelligent systems for ballistic impacts will soon be developed and optimised in our laboratory thanks to our already developed expertise in the field of quasi-static tensile stress monitoring using flexible textile sensors.

11.5 Conclusion

A new textile composite solution, made as part of a final target, was found to resist ballistic impact well. This result was mainly due to the introduction of 3D warp interlock fabrics, stacked together with ceramic tiles to absorb the energy during the impact of 12.7 mm armour piercing ammunition at a speed of 610 m/s. A new sensor yarn, introduced in a 3D warp interlock, has been developed for on-line monitoring of quasi-static tensile stresses. The fibrous sensor yarn is able to detect strain in the composite part and thus acts as an *in-situ* strain gauge. This important innovation will lead some way towards the development of intelligent textile sensors and related data acquisition modules for real time *in-situ* monitoring of energy dissipation in composites for armoured plating. It is expected that these innovations and their integration for the development of intelligent armoured solutions will help us better understand the real behaviour of the final target. The next step in our research thus constitutes the development of sensors capable of detecting high-speed ballistic impacts when embedded inside armoured plating.

11.6 Future trends

Intelligent textiles for armoured vehicles could be widely used in the future to better protect and adapt the armouring against not only conventional and NATO certified ammunitions, but also against non-conventional weapons such as IEDs. The armouring shape of the vehicle could be made auto-adaptable so as to change the form of the vehicle when faced with threats detected immediately by sensor yarns. In this way, mechanical stress and energy absorption could be actively managed during the impact. This could lead to better use of different active and passive materials, combined in the armour to resist against different types of ballistic impacts.

Structure modifications can be observed during the impact, using an auto-adaptive material such as a shape memory alloy. This has the capacity to change from a martensitic to an austenitic phase under different ambient conditions (including temperature and mechanical stress). The main difficulty lies in the capacity of these materials to be effective against high-speed impacts and their ability to react within a suitable time frame.

Maintenance of vehicle armour could be facilitated by the use of *in-situ* sensor yarns, as these yarns can detect damaged zones and the extent of the damage. This could help minimise down time, reduce maintenance costs and avoid undue loss of personnel and material in the battle field. Another interesting feature that could be developed in the future for better protection of vehicles in a battle field includes the ability to immediately change colour using active chemical agents or reproduced 'biological molecules' (as contained in octopus skin), driven by high-speed electric pulses generated by sensor yarns. This perspective helps firstly to adapt the colour of the vehicle in the human visible range to its environment and secondly to spread the signal detection to UV or IR frequencies. Active camouflage solutions could be developed through the use of sensor yarns.

11.7 References

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