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RESEARCH IN TEXTILE COMPOSITES AT K.U. LEUVEN

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ABSTRACT

An overview is presented of the research on textile composites at K.U. Leuven. Investigated are three dimensionally woven sandwich fabric preforms for delamination resistant sandwich structures, velvet woven 2.5 dimensional fabrics for delamination resistant laminates and knitted fabrics with good drapability for laminates of complex shape.

INTRODUCTION

Textiles for composites have been around since cotton fabrics were impregnated with resins to protect the fragile mummies in Ancient Egypt. Also, soon after the introduction of glass fibres in the thirties, woven glass fabrics were used to reinforce thermoset resins. The same happened with carbon fibres in the sixties.

For decades however, the type of textile used as composite reinforcement was limited to plain or satin weaves. After initial (mainly military) developments for very specific applications, it is only since the early eighties that new textiles are especially designed for composite applications. This brought along a fundamental communication problem: the world of deniers, decitexes, warps and wefts had to be connected to the world of MPa's, ksi's, quasi-isotropic laminates and CAI. Textile people had to listen to the specific requirements of an engineering material, and composites engineers had to get acquainted with the possibilities and limitations of the textile technology.

In the United States and Japan as well as in Europe, a small number of universities have played a key role in bridging this originally wide gap between the worlds of textile and composites. Some of these university research groups had a background in textile engineering, but it might be surpising that the majority had no connections at all with textiles. They discovered the textiles world while looking for more efficient fibre preforms - more efficient in mechanical properties as well as in processing.

At the Katholieke Universiteit Leuven (Belgium), no background in textiles was present when an occasional contact with a Belgian weaving company revealed the possibilties of using the velvet weaving technique for specific composites applications. We suggested to the weaving company not to cut the pile threads when the fabric leaves the loom, like is done in classic velvet weaving (see figure 1). In this way, a double layer fabric, in which both layers are connected, was obtained, and it was found that this 3D-fabric was the ideal preform for sandwich structures [1-2]. Moreover, the velvet type fabric was seen as a potential material to solve the longstanding problem of the low interlaminar fracture toughness of composites: the short fibres, sticking out of the 2D-fabric could act as crack deviators, hence increasing the energy dissipation during crack growth. Because the fibres sticking out of the 2D-fabric were in fact cut, we jokingly called them 2.5D-fabrics, a name which has since then been taken over seriously by other authors.

Preliminary experiments showed that our hypotheses were valid: delamination resistant laminates were manufactured using the 2.5D-fabrics [1-3], and light, stiff and impact resistant sandwich beams were made out of the 3D-fabrics. To investigate more in depth the advantages and potential applications of the 3D-fabrics, a European wide project, supported by the European Community in the framework of the BRITE-EURAM program, was started. Belgian, Dutch, German, Italian and Spanish companies and universities are now collaborating in order to further optimise the fabric geometry and the processing of the 3D-fabrics.

Once our interest was raised for advanced textiles, we actively looked for other existing, well established textiles technologies, which could be introduced into the composites community. To our surprise, almost no reports could be found on the use of knitted fabrics in composites, although the potential advantage of superior drapability was obvious. Cooperation was started with a Belgian knitting company, and soon it was found that knitted fabrics indeed represent an interesting compromise between acceptable mechanical properties and superior drapability [4], moreover, excellent impact resistance as was recently discovered.

In the following paper, a general overview is presented of five years of research in textiles for composites. The paper is really meant as an overview; more detailed information on processing and on mechanical properties can be found in the papers mentioned in the reference list.

3D SANDWICH FABRICS

The sandwich fabric is produced by a variant of the classic velvet weaving technique (see fig. 1), which is used for the production of corduroy textiles. In the case of velvet production, the resulting distance fabric is cut in two, leading to two soft surfaces of pile fibre ends. By skipping this last action, the sandwich structure is retained. In figure 2 the structure of the fabric is shown and a picture is included of the view of the fabric in warp direction. In the standard fabrics glass fibres are used.

The main advantage of the use of this material in sandwich composites is the fact that the pile fibres in the core (which determine the 3D character) bind the skins of the material together, thus hindering the delamination between skin and core. Compared with more traditional sandwich structures with a honeycomb or foam core, the structure has a much higher delamination resistance. Honeycomb structures only have a small contact surface to which the skins adhere; foam cores do delaminate fairly easy in the zone just below the adhesive layer.

Production methods

The sandwich fabric can be impregnated with resin rather easily, with the same equipment that is being used for 2 dimensional textiles. Until now primarily thermoset resins like polyester, epoxy and phenolic resin have been used, depending on the application. The production of the final, cured structure can be done in various ways (see fig. 3).

Especially for applications in the polyester industry, where the material is primarily used as core material in laminated products, the material is cured without further treatment. It can be laminated in the same way as normally used glass mats or fabrics. As only limited core thicknesses (up to 6 mm) are used and the pile fibres are quite resilient, the pile fibres will almost completely stretch themselves after impregnation. A useful sandwich structure is obtained in this way. Additional layers of 2 dimensional fabrics or glass mats are used to obtain thicker skins with a higher flexural stiffness. Also to obtain a smooth outer surface it may be necessary to add an additional layer.

For higher pile lengths (above 15 mm) it is necessary to do a stretching operation to counteract the buckling of the pile fibres under the weight of the upper skin. The Italian company Metalleido, member of the Aficoss-team, has developed a mechanical stretching process to realize fully stretched and perpendicularly aligned pile fibres. The same result can be obtained by injecting an expanding foam in the core, which stretches the pile fibres.

The use of foam in the core is optional. Until now polyurethane and phenolic foams have been used. Next to the potential use to stretch the pile fibres, the foam is also applied for structural reasons (reinforcement of the core), for its contribution to energy absorption during impact or for other reasons as the watertight sealing of the core or for isolation purposes.

Applications

Applications of the material are found on a large scale in the polyester composite industry. Examples are sidespoilers for trucks, panels for train compartments and a tankwall through which leaking fluids can be drained.

When introducing a new type of material, the properties and price have to be compared with existing materials and other materials in development. Our material has interesting opportunities in areas where there are no extreme demands for mechanical properties and especially for mechanical properties by weight, that is mainly outside of the aerospace industry. In the polyester industry high resin weight percentages of around 60% can be used to support the pile fibres at their 'feet' and still light structures do result. The same does account for applications which are presently being studied, using epoxy and phenolic resin.

Properties

To produce panels with a high flexural stiffness, sandwich fabrics with a larger core thickness have to be chosen. Once more it is stated that to counteract collapse of the fabrics under their own weight, innovative production techniques have to be used. The mechanical properties can be further improved by injecting a stiff foam in the core. For fabrics with a thickness above 15 mm the use of a foam is even indispensible. The foam does increase the weight but still very light panels are obtained. In figure 4 the 4 point bending stiffness of 10 and 20 mm thick panels is compared, impregnated with epoxy resin and partly foamed up with polyurethane. The densities of the materials are about 230 kg/m^3 for the 10 mm thick panels (core density 45 kg/m^3) and around 130 kg/m^3 for the 20 mm panels (core density 40 kg/m^3), without foam.

The shear resistance of the material is a weak spot. The shear resistance is especially of importance when short spans are used during flexural loading. For short spans the greater part of the deflection is caused by shear in the core. In the pictures in figure 5 clearly the shearing of the 20 mm thick structure can be seen, while the material, having part of the pile fibres woven under an angle of 45 degrees, shows much more true bending behaviour. At larger spans the stiffness of the skins will be of increasing importance for the flexural resistance. The data in figure 4 for the 4 point bending stiffness have been obtained for a relatively short span of 200 mm. The total deflection has been attributed to true bending. The low shear stiffness is thus contributing heavily to the values. In this way the values are conservative guesses for the flexural stiffness of larger panels. It is not possible to relate the flexural stiffness of the material directly to the one of honeycomb structures, as the stiffness of the honeycomb depends on the type of adhered skin. The comparison thus has to be made on the basis of the compressive and shear properties.

For certain applications the material could replace honeycomb structures, because of the mentioned strong improvement of the delamination resistance between skin and core and the high cost of honeycomb structures. In figure 6b the measured skin peel strength is shown, which can be used to compare the resistance against delamination [5]. The fact that skin peel strength values up to four times as high as those for honeycomb structures have been found (for high pile density material with 50 piles/cm^2) can be attributed to the fact that the skins are connected to each other by the pile fibres. The fibres have to be broken before skin separation occurs.

For the compressive strength comparable values are obtained as for commonly used aramid fibre paper phenolic resin honeycombs (Nomex), of comparable density [6]. In figure 6a the compressive strengths of various materials are shown. When comparing with honeycombs the properties have to be related to the density of the material. In this case the proper comparison is made by relating to the core density. The specific compressive strengths of the various 3D materials are comparable to the reference honeycomb material.

The shear strength of the 3D sandwich material of 10 mm thickness in standard configuration with perpendicular pile fibres is only one fourth of the shear strength of a comparable aramid fibre paper phenolic resin honeycomb. By weaving part of the pile fibres under an angle of 45 degrees this difference can be halved.

Modelling work

Because the mechanical properties of the sandwich structure are highly dependent on the constitution, especially on the fabric geometry, it is useful to develop models to depict the influence of the various parameters. This is one of the major goals of the research at KU Leuven. The work is carried out in cooperation with the University of Zaragoza (Spain) and Drexel University (USA).

In the first place the parameters are studied which determine the behaviour of the core, as there are the pile fibre length, density, angles, geometry, the possible support by resin at the pile feet and contact points of the pile fibres, and the reinforcement of the core by a foam. The core is divided in subcells which contain one pile bundle. The bundle is segmented. To calculate the stiffness matrix, the stiffness matrici of the elements are combined by assuming either constant stress or constant strain, depending on the loading situation. Also the foam support can be included.

Further, the stiffness of the used fabrics in the skins is modelled. Again, the structure is divided in subcells with their characteristic contribution to the stiffness matrix.

The global composite stiffness is calculated using the "fabric geometry model". First results of this model calculation are presented in [7].

2.5 DIMENSIONAL FABRICS

As is well known, the out of plane properties of laminates are much lower than the in plane properties, by the lack of reinforcement in the third direction. Delaminations between layers, for instance after impact loading, are a major problem. Various solutions have been suggested, but they very often have a drawback on other mechanical properties. For instance, the use of a tough interlayer does improve the delamination resistance, but leads to a decrease of the shear modulus.

The growth of delaminations can be hampered by diverting the crack front and by inducing pull out of fibres in the delaminating zone. This is what is done by using 2.5 D fabrics.

Production

The 2.5 D fabric is produced with the same velvet weaving technique as is being used for the 3D sandwich fabric (fig.1). At the end of the weaving process the pile fibres are cut and two hairy, plain weavings result, which have the pile bundles sticking in the third dimension (fig. 7). As for the 3D fabric, pile fibre length and density can be varied.

The fabrics can be impregnated with resin, laminated and cured by conventional production methods. It appears that the in plane properties of the laminates do not decrease by the addition of the pile fibres. For certain properties, like the tensile strength, even a slight increase is observed.

Various fibre types can be used; in the research conducted at KU Leuven, use was made of carbon and glass fibres as fabric material and glass and aramid fibres as pile material.

Properties

The delamination resistance of a material is tested by means of fracture toughness tests, based on an analysis of fracture mechanics. In this approach the energy is calculated for delamination growth over a certain area, expressed as the material parameter G_C, the fracture toughness. Three modes of fracture propagation are considered: mode I, which is a crack opening mode under tensile loading, and modes II and III, which are two types of shear mode.

In our research mode I tests (DCB tests; see fig. 8) and mode II tests were performed. The results have been reported in reference 3. The 2.5 D laminates were compared with similar fabrics without pile fibres.

The results of mode I tests on pure glass fabrics are shown in figure 9. The sharp increase in fracture toughness in the presence of pile fibres is evident. In the case of carbon fabrics similar results are obtained (fig. 10). The increase in fracture toughness is caused by the fact that the propagating crack, which runs through the matrix when using plain weave fabrics, is now hindered on its way by the pile fibres. This means that the bond between pile fibres and resin has to be broken and that pile bundles have to be pulled out of the resin. The dissipated friction energy can be modelled and is given by the following formula:

$$G_C = G_{C,p}(\text{plain}) + \frac{n\, 2\pi\, r\, l\, G_{C,int}}{100}$$

The second term describes the extra energy absorption by the presence of the pile fibres (r is the fibre bundle radius, l the pile fibre length, n the number of pile bundles per cm^2 and $G_{C,int}$ the fracture toughness of the fibre matrix interface).

Besides the fracture toughness also the impact behaviour of 2.5 D laminates has been studied. Here especially the residual compressive strength after impact is of interest. Figure 11 shows that the normalised compressive strength after impact for most 2.5D laminates is higher than the value for plain weaves. Furthermore, the absolute strength values do not decrease in case the impact energy is doubled.

Conclusion

Our results show that the use of 2.5 D fabrics leads to an improvement of the delamination resistance. Both fracture toughness tests and compression after impact tests do show this. The improvement is obtained without affecting other material properties and without a change in production method. This imposes major advantages over plain weave fabrics in applications where delamination resistance and impact resistance are of interest: in the aerospace industry, but also in e.g. ship building.

KNITTED FABRICS

The fundamental difference between woven fabrics and knitted fabrics is found in the way the fibres are interconnected. Woven fabrics feature straight yarns in plane and only show out of plane curvature at places where the yarns cross. Knitted fabrics however, feature the interconnection of yarns by loops, leading to strong curvature in the plane of knitting.

This fact would suggest that the mechanical properties of composite materials reinforced with knitted fabrics will differ largely from the properties of woven fabric composites. Both stiffness and strength would be negatively influenced by the curvature of the fibres. On the other hand, one could expect that by stretching the loops, the materials would be very flexible in shaping. These two hypotheses were the basis of our research.

Production

Starting point was a knitted glass knit fabric, with a surface density of 455 g/m^3. The material was developed by the NV Saturn, a daughter company of the NV Wydooghe, Izegem Belgium. The structure is such that the yarns have a preferential orientation in warp and weft direction (although these weaving terms are strictly not being used for knitted textiles).

The knits were impregnated at KU Leuven with epoxy resin and cured to B-stage. These prepregs were laminated to lay-ups of 1,3,6 and 10 layers and cured in an autoclave at 140° C under a pressure of 7 atmosphere. To evaluate the mechanical properties, tensile tests were performed parallel to, perpendicular to and under an angle of 45 degrees with the direction of knitting.

Properties

The stiffness shows a remarkable isotropy: in the three tested loading directions the Youngs modulus is about equal (fig. 12). This is a distinct advantage over fabrics, which show a decrease in stiffness in the diagonal direction up to 40%, compared with warp and weft direction. The degree of anisotropy of knitted fabrics can be controlled by adjusting the knitted structure.

In figure 12 it can be seen that the number of layers in the laminate has a significant influence on the stiffness. This is also shown in figure 13a; the same effect is also found for the strength (fig. 13b). There are two reasons for this effect. In the first place, the fibre volume fraction will increase with the number of layers. Knits are fairly open structures and in a composite of only one layer the holes between the yarns have to be filled with resin. By using more layers the yarns of adjacent layers will fill each others holes, leading to a higher fibre volume fraction. The second reason also has to do with this effect: the filling of holes in adjacent layers leads to a mechanical interlocking of yarns and thus to an improvement of stiffness and strength.

In figure 13 also a comparison is made with woven fabric composites and with glass mat reinforced composites. Above three layers of knitted textiles, stiffness and strength approach the values of fabric composites and are double as high as the values for mats. This shows that knits are an attractive compromise: they combine the freedom of shaping of discontinuous fibre composites with the good mechanical properties of woven fabrics. Put differently: by using knits one can circumvent the poor mechanical properties of mats and the limited drapability of fabrics.

The good drapability of knitted textiles had an additional positive effect. In a simulated experiment knits were stretched for 30% and subsequently cured. In the loading direction an increase of stiffness and strength of 45% was found, while the properties perpendicular to the stretching direction hardly changed (fig. 14). This shows that draping can only improve the mechanical properties. Furthermore, the degree of stretching poses an additional possibility to control the anisotropy in mechanical properties, next to the adjustment of the knitted structure.

CONCLUSION

In this review paper, developments in textiles for composites, achieved in the Department of Metallurgy and Materials Engineering of the K.U. Leuven have been presented.

A new type of sandwich structure has been developed, based on double layer fabrics. The structures show good and tunable flexural stiffness and compression strength, and excellent skin peel strength. In this way, they can compete with honeycomb and foam core sandwich structures, certainly in those applications where cost is the key factor in materials selection.

A solution was presented for the long-lasting problem of the poor delamination resistance of composite laminates. It was shown that composites based on 2.5D-fabrics have a higher interlaminar fracture toughness and superior compression-after-impact values.

Finally, it was proved experimentally that the belief that knitted fabrics are useless for composites is based on an unfortunate prejudice. Both stiffness and strength of knitted fabric composites are in between the values for woven fabric and random mat composites, but the major advantage is their superior drapability compared to both these materials.

It is believed that creative thinking will find more ways to use "old" textiles in the "new" world of composites.

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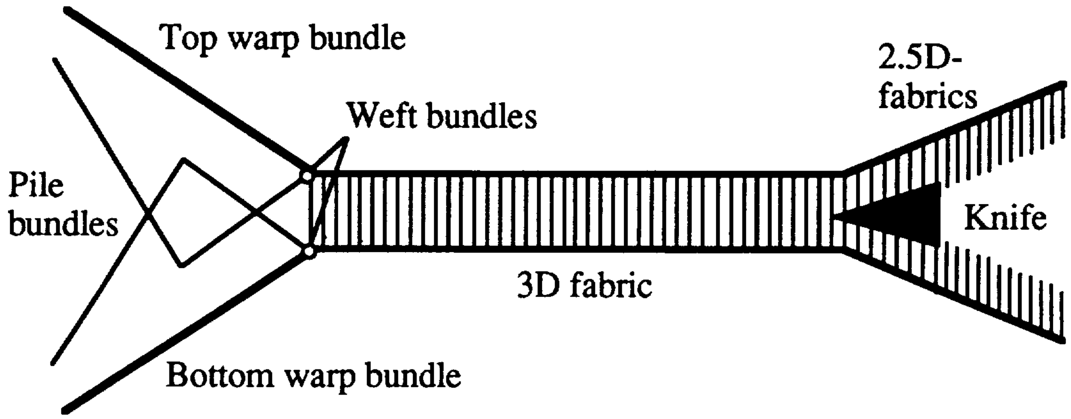
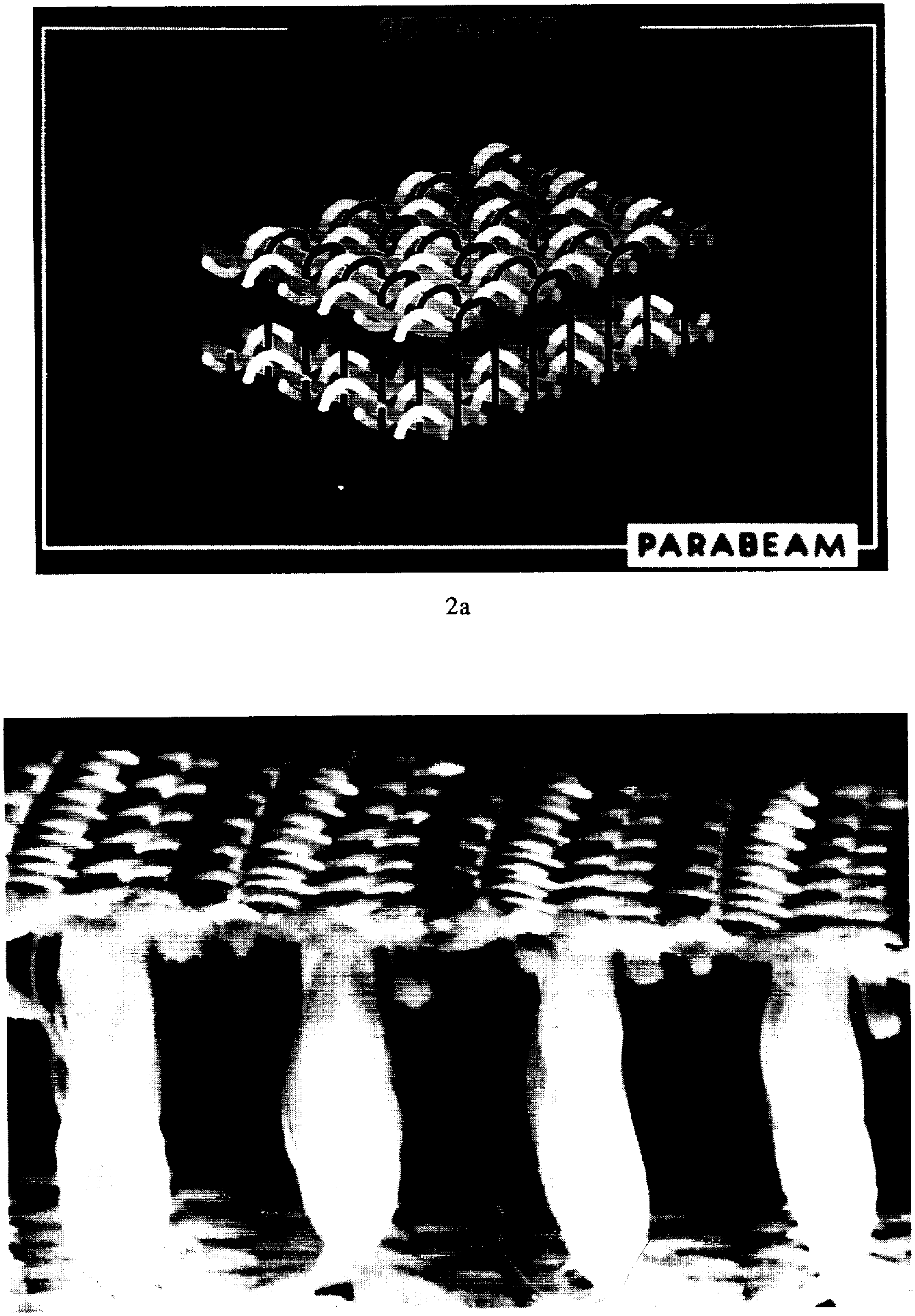


Figure 1: Production process of a 2.5- and a 3-dimensional fabric.



2a

2b

Figure 2(a & b): Schematic representation and photograph of a three-dimensional fabric.

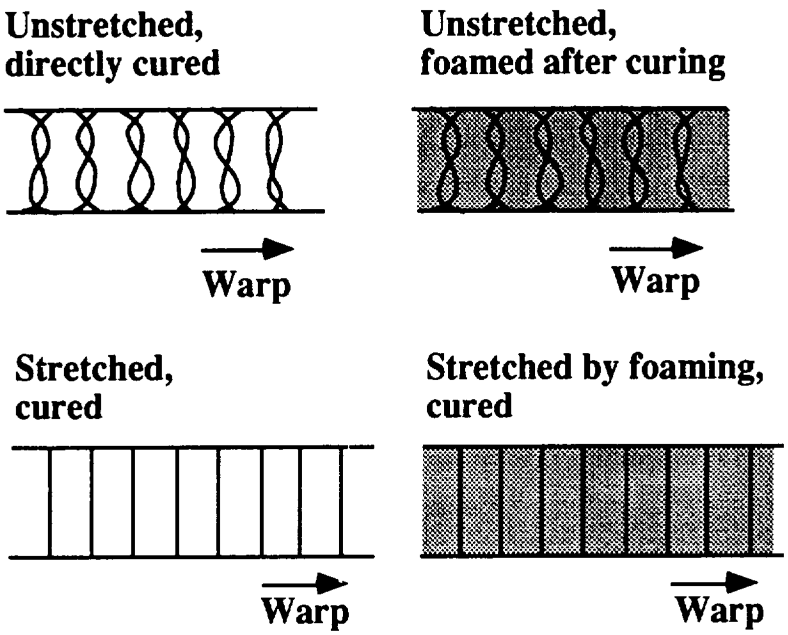


Figure 3: The end shape of the panel can be different (unstretched without foam, stretched without foam, unstretched with foam, stretched with foam).

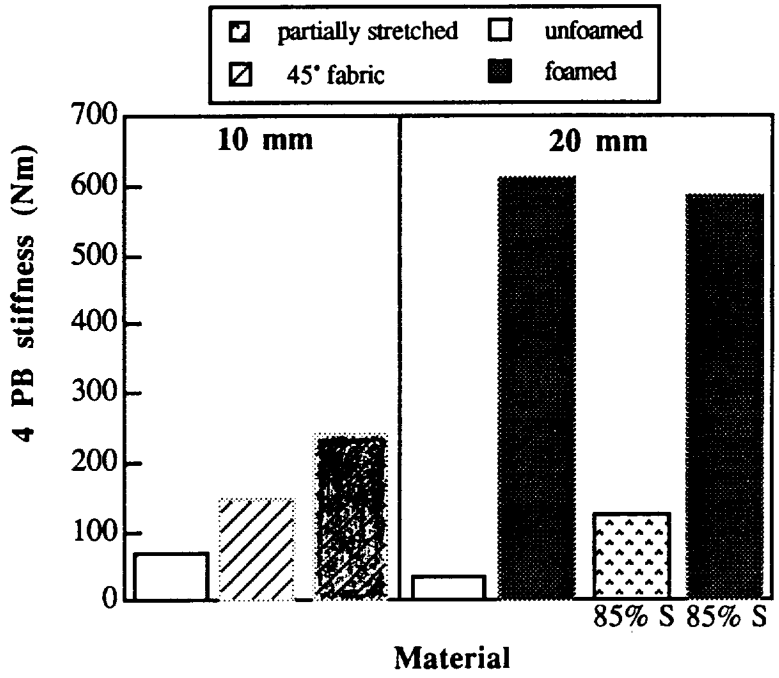
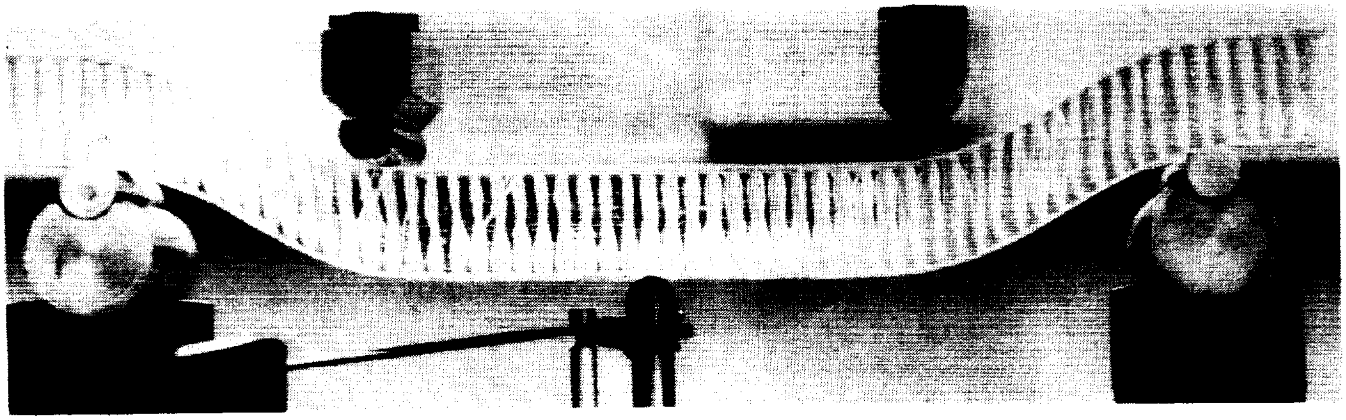
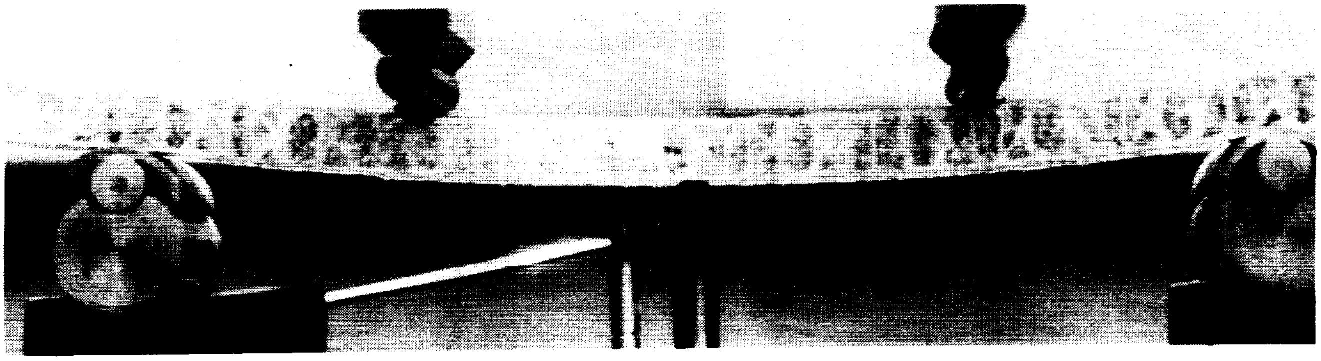


Figure 4: 4 point bending stiffness (span length 200 mm) for two different pile lengths (10 and 20 mm) and pile density 25 piles/ cm^2. The results are normalised to the width. The specimens were tested in the warp direction (resin content 55% by weight; foam density 60 kg/m^3).



5a



5b

Figure 5(a & b): Photographs of the deformation of an unfoamed specimen and a foamed specimen with 45° pile fibres: the deformation of the first sample is mainly caused by shear deformation. The specimen with the 45° pile fibres has only a low amount of shear deformation.

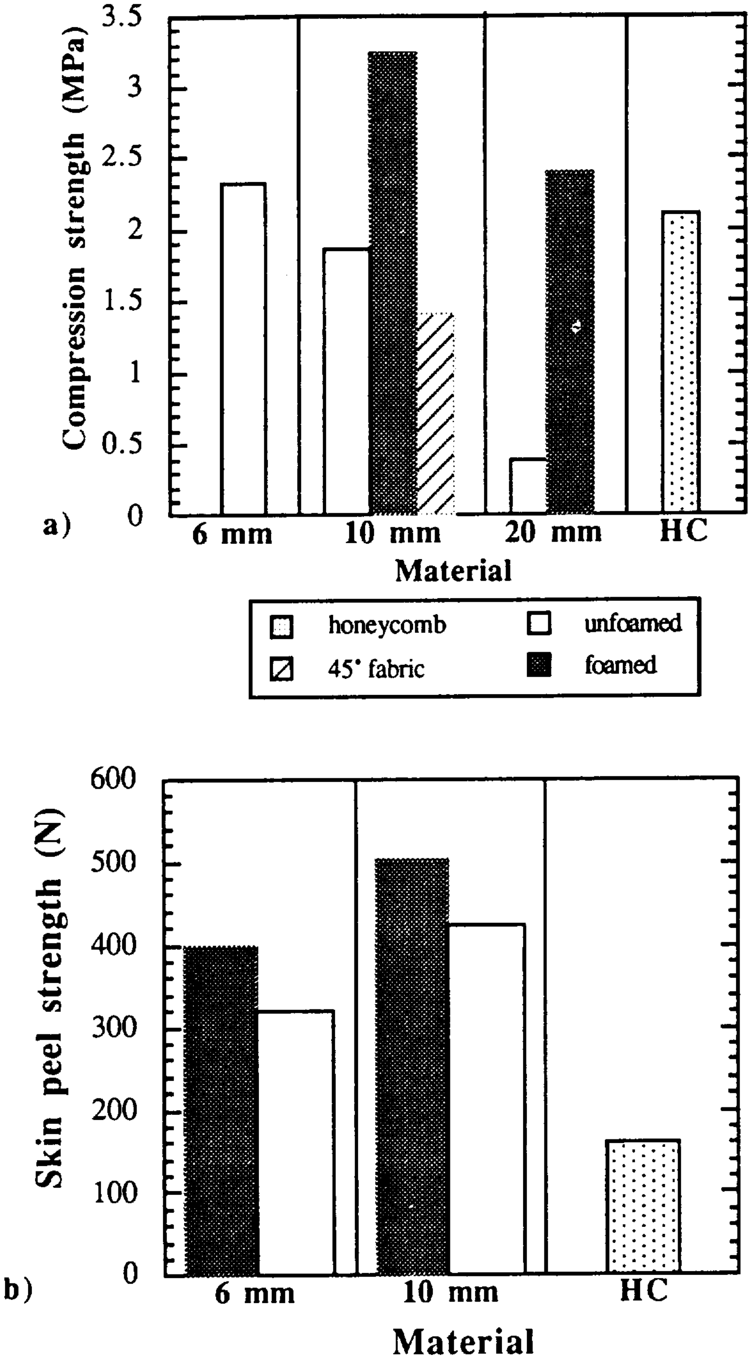


Figure 6: Flat compression strength (a) and skin peel strength (b) of different 3D sandwich panels with different pile lengths (6, 10 and 20 mm). As a comparison the values for a honeycomb structure (Nomex®) were also included.

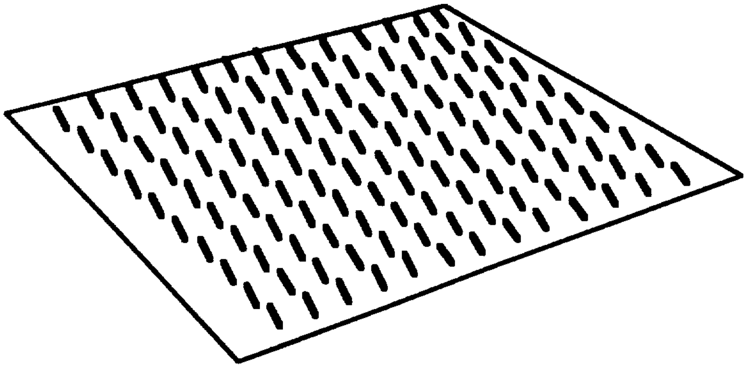


Figure 7: Schematic view of a 2.5D fabric. The pile bundles are not standing up, but are lying down.

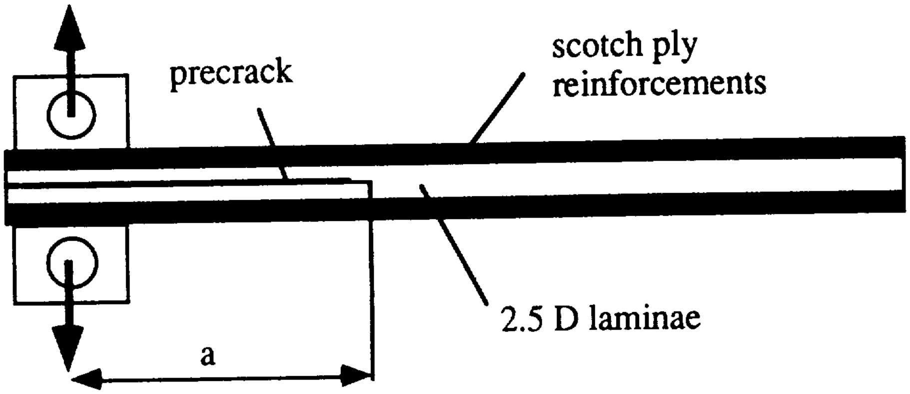


Figure 8: Double Cantilever Beam Specimen (mode I type of loading).

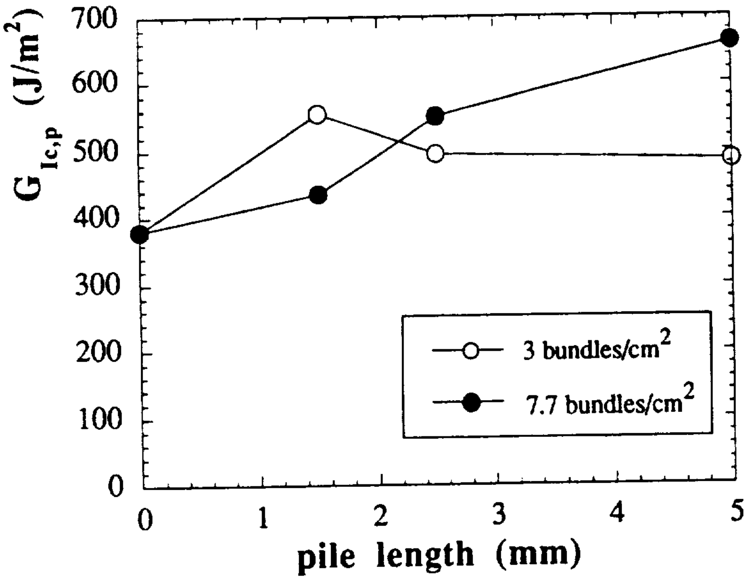


Figure 9: Mode I fracture toughness of 2.5D glass fabric laminates as a function of the pile length and pile density (in number of bundles per cm^2).

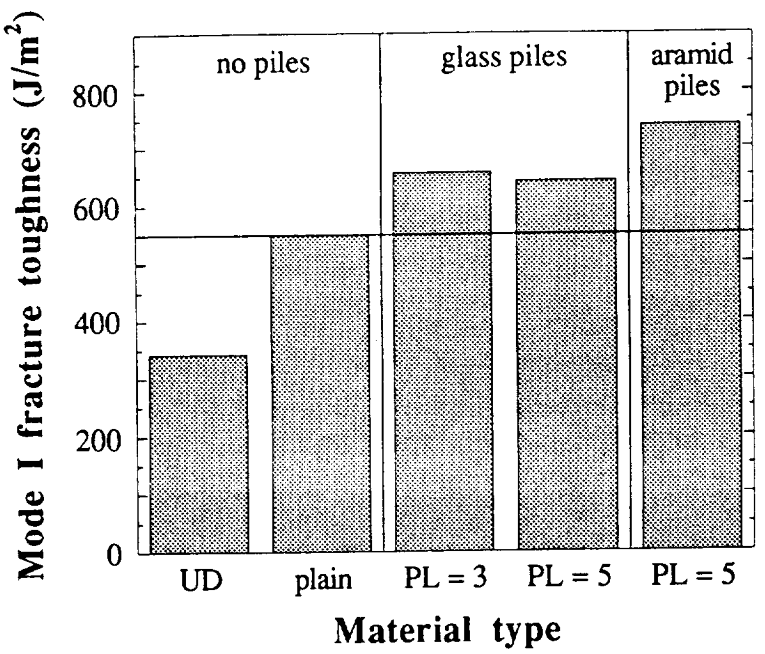


Figure 10: The mode I fracture toughness of 2.5D carbon fabric laminates with glass and aramid pile fibres, respectively, as a function of the pile length (PL). As a comparison, the fracture toughness of a unidirectional composite is added.

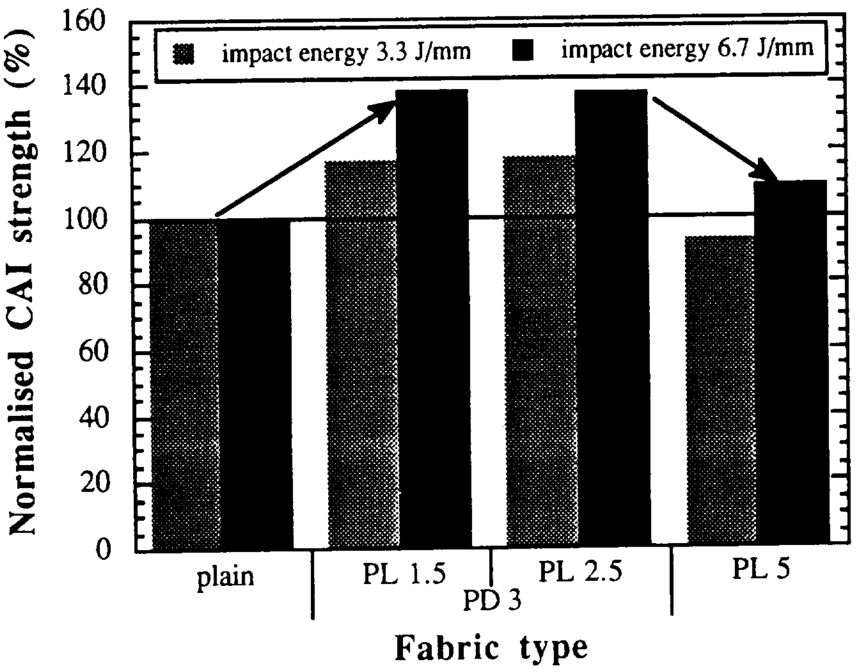


Figure 11: Compression strength after impact for different materials with two different impact energies (PL is the pile length in mm, PD is the pile density in number per cm^2). The tests were performed on pure glass fabrics.

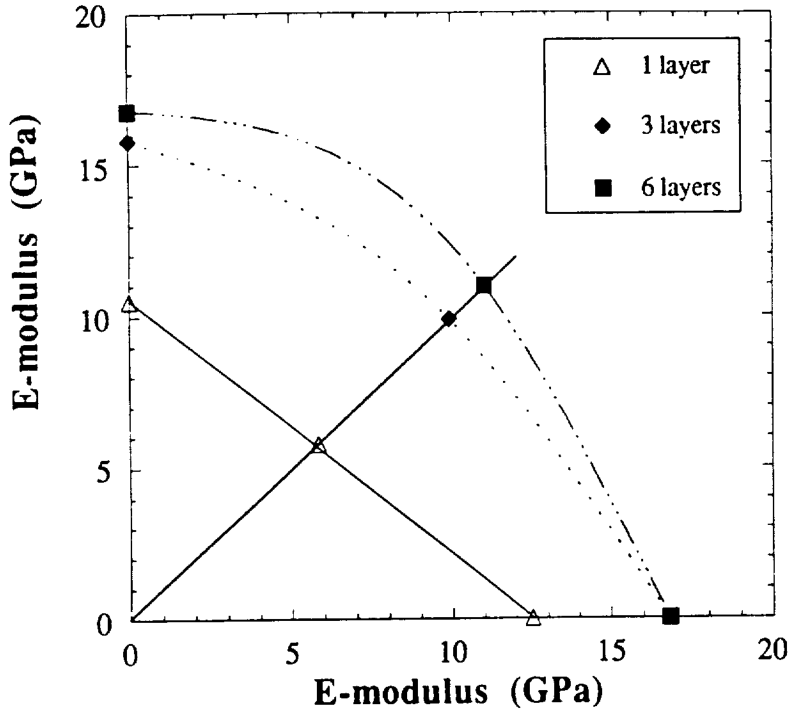


Figure 12: Stiffness of a knitted fabric composite in different directions.

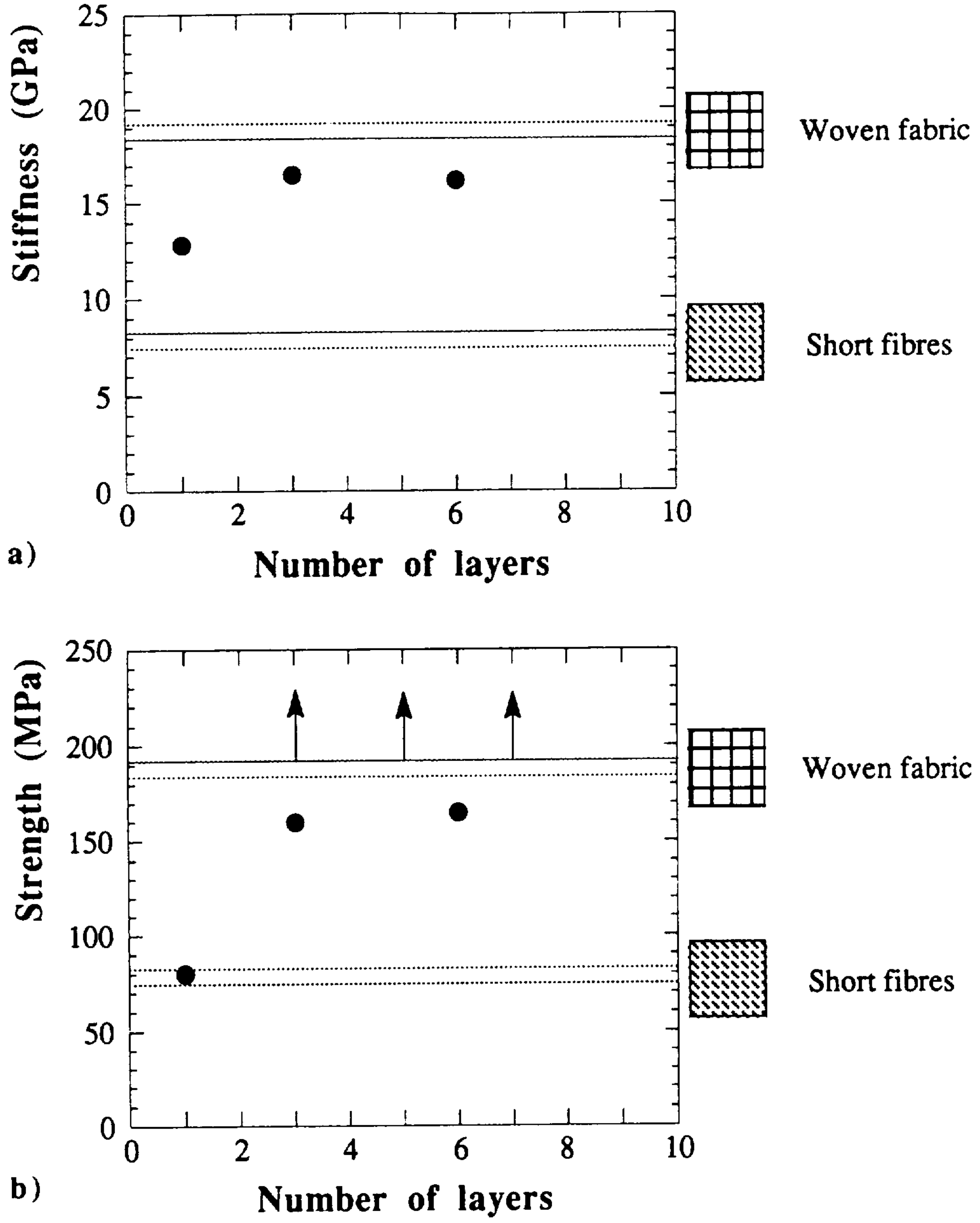


Figure 13: Stiffness (a) and strength (b) of knitted fabric composites in comparison with woven fabric and short fibre composites.

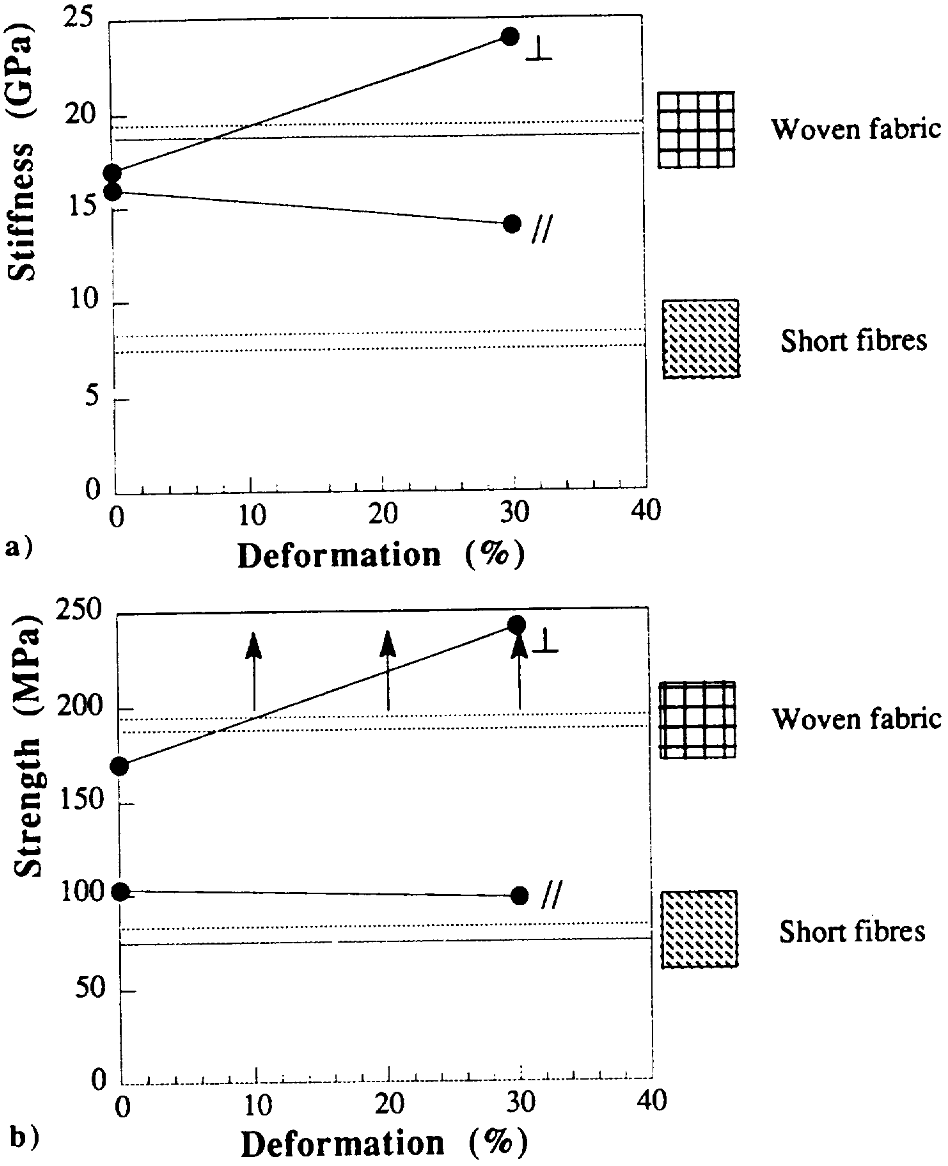


Figure 14: Influence of the deformation on the stiffness (a) and strength (b) of knitted fabric composites.