# Introduction: Why are 3-D textile technologies applied to composite materials?

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Composite materials have been used for the past 30 years in many sectors such as aeronautics, space, sporting goods, marine, automotive, ground transportation and off-shore. These materials emerged in such areas because of their high stiffness and strength at low-density, high-specific energy absorption behaviour and excellent fatigue performance.

Among the main limitations of these materials, however, are their high cost and the inability to have fibres in the laminate thickness direction, which greatly reduces damage tolerance and impact resistance.

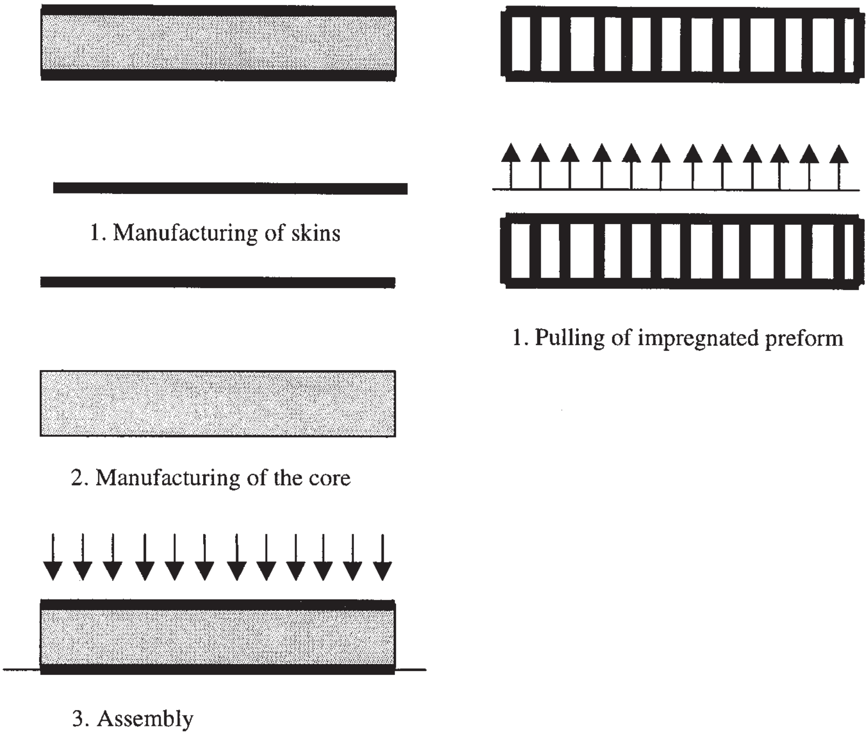
## Manufacturing costs

3-D reinforced composite materials are manufactured by impregnating a preform. This issue is critical in terms of manufacturing costs, since the process is reduced and simplified in comparison with traditional manufacturing technologies.

Figure 1 represents the manufacturing steps of a standard sandwich composed of two skins and a core (left) and a warp knitted structure (right). The warp knitted sandwich structure has arisen as an efficient configuration for applications where interlaminar stresses (peeling or interlaminar shear) are critical. The warp knitted sandwich structure is characterized by having a series of fibres in the thickness directions or plies, which bridge the top and the bottom skins (Fig. 1, right).

The standard sandwich requires three steps to be manufactured. First, both skins must be made. Hand lay-up or vacuum bag processes may be used for this purpose. Second, the core must be manufactured: honeycomb or foam materials are usually applied for the central part of the sandwich construction. Finally, the three sub-structures must be assembled by means of vacuum bag or press technologies. The foam may also be injected once the skins are positioned in the tooling.

The manufacturing process of a warp knitted sandwich structure is much simpler and, therefore, much cheaper. The impregnated preform is pulled



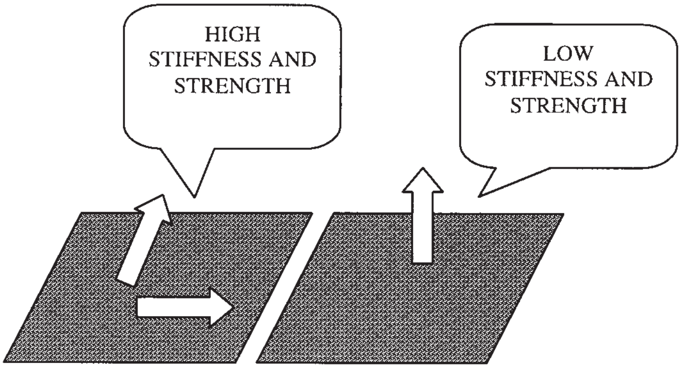
*1* Manufacturing steps of standard sandwich (left) and warp knitted sandwich structure (right).

until the top skin reaches the design height. The resultant warp knitted sandwich is an extremely efficient structure in terms of peeling, shear, impact, damage tolerance and energy absorption behaviour, as we will show in this book.

## The problem in the thickness direction

The first generation of composite material consists of a number of plies composed of a matrix and unidirectional fibres oriented in a certain direction. This concept of laminate is very efficient since the fibres may be oriented in the optimal directions. However, there are a number of associated problems: the two directions perpendicular to the fibres showed very low stiffness and strength.

This problem became a key issue for the composite material designers, since in-plane transverse strains and stresses appeared in many cases. In static conditions, when multidirectional loads were applied, the in-plane transverse stresses generated premature matrix cracking in the transverse



*2* Stiffness and strength in the plane of the ply (left) and out of the plane (right).

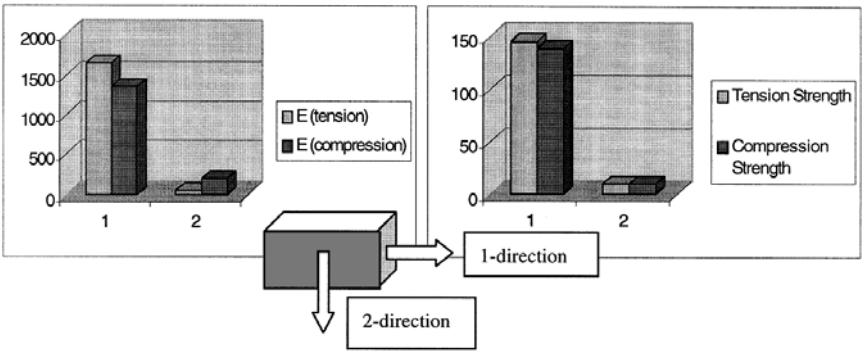
directions. In fatigue analyses, matrix crackings were also reported for a low number of cycles. In crash problems, non-linear deformations occurred owing to the low strength and stiffness in the in-plane transverse direction and, finally, dynamic studies concluded that these transverse properties induced low natural frequencies and therefore low dynamic stiffness of a large number of composite structures.

To overcome this problem, two solutions were proposed:

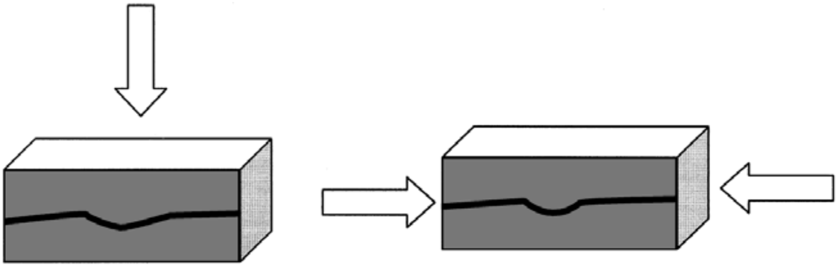
- The implementation of multidirectional laminates.
- The use of 2-D fabrics.

2-D reinforced composite materials were implemented because, by means of this typology, the two perpendicular directions were covered with fibres and, therefore, the weakness of the in-plane transverse direction vanishes. Not only were bidirectional fabrics [0/90] implemented, but multidirectional 2-D fabrics were also incorporated in order to increase stiffness and strength in a number of directions: [0/60/–60], [0/45/90/–45], etc. By using multidirectional plies or 2-D fabrics, it is possible to optimize the directions of the fibres in the plane of the ply. However, the perpendicular direction to the plane of the ply exhibits very low stiffness and strength (Fig. 2).

Figure 3 shows the values of elastic moduli and strengths (MPa) in tension and compression of a carbon fibre/epoxy matrix unidirectional laminate in directions 1 (longitudinal) and 2 (thickness direction). As expected, both tension and compression elastic moduli and strengths are much higher in direction 1 than in direction 2. This problem is a major one in those cases where out-of-plane stresses are predominant over in-plane stresses. Generally speaking, when the laminate is thin and the case is static, the in-plane stresses are the most important components.



*3* Comparison of elastic moduli and strengths in MPa (tension and compression) in 1- and 2-directions.



*4* Delamination due to an impact transverse load (left) and compression after impact (right).

However, the three out-of-plane stress components (peeling and the two interlaminar shear components) can become critical if the following conditions are applied:

- Thick laminate
- Fatigue loading
- Dynamic effects
- Impact loads
- Crash problems
- Stress concentrations

Figure 4 shows a delamination failure due to an impact transverse load (left) and a compression after impact loading case (right). For those cases, the 3-D fabric reinforcement provides a solution to the problem detailed above.

The manufacturing costs are considerably reduced when using 3-D textile reinforced composite materials, which are obtained by applying highly productive textile technologies in the manufacture of fibre preforms.

*Table 1* Comparison of stiffness and strength properties of a standard sandwich structure and a warp knitted sandwich structure

| | Standard sandwich | | | Warp knitted sandwich | | |
|---|---|---|---|---|---|---|
| | Core | Height: | 50 mm | Core | Height: | 50 mm |
| | | Material: | polyurethane foam $\rho$ = 40 kg/m$^3$ | | Material: | polyurethane foam $\rho$ = 40 kg/m$^3$<br>Plies each 5 mm ($d$ = 0.6 mm) |
| | Skins | Thickness: | 2 mm | Skins | Thickness: | 2 mm |
| | | Material: | E-glass/ polyester (0°/90°) fabrics $V_f$ = 30%[a] | | Material: | E-glass/ polyester (0°/90°) fabrics $V_f$ = 30%[a] |
| Bending stiffness EI (N/mm$^2$/mm length) | $25 \times 10^6$ | | | | $25 \times 10^6$ | |
| Maximum bending moment (N mm/ mm length) | 812 | | | | 812 | |
| Peeling strength (N/mm$^2$) | 0.51 | | | | 23 | |
| Interlaminar shear strength (N/mm$^2$) | 0.28 | | | | 10 | |

[a] $V_f$ = fibre volume fraction.

The damage tolerance and the impact resistance are also increased since the trend to delamination is drastically diminished because of the existence of reinforcements in the thickness.

Nowadays there are a number of manufacturing techniques available for composite materials:

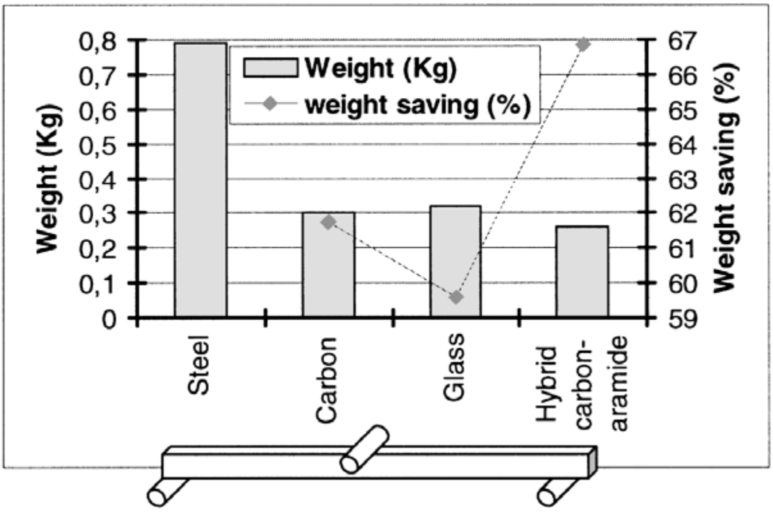
- Braiding
- Stitching
- Warp knitting
- Weft knitting
- Weaving

These textile technologies have made possible a second generation of composite materials, specially designed for bearing high stresses in three directions, impact, crash, energy absorption and multiaxial fatigue.

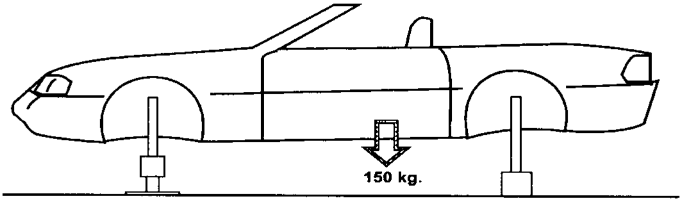
Table 1 represents the results of both configurations in terms of bending stiffness, peeling and interlaminar shear effects. The values of the bending stiffness are similar, while the interlaminar strengths are two orders of magnitude higher for the warp knitted sandwich structure, owing to the existence of the plies oriented in the thickness direction.

## Examples of application

A comparison study between different material systems has been carried out in order to assess the weight saving in a 3P bending crash of a box beam. Braided carbon, glass fibre and a hybrid carbon–aramide system were compared with steel (Fig. 5). The maximum weight saving was obtained by the braided hybrid carbon–aramide system (67%). Also 61% and 59% of weight saving were also reported for carbon and glass fibre materials respectively. The floor of a vehicle was studied by using several material systems. The width of the floor was 1.2 m and the length was 1476 m. Both bending and torsion moment load cases were studied (Figs. 6 and 7, respectively). For the bending case, the maximum rigidity corresponded to the

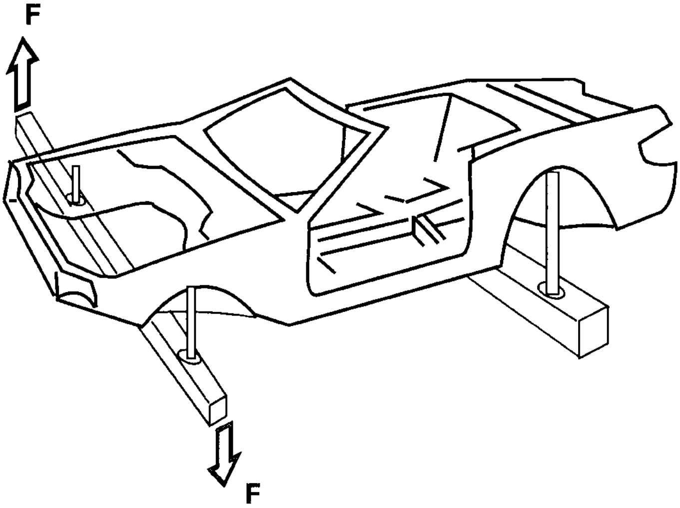


*5* Weight and weight saving of various material systems.

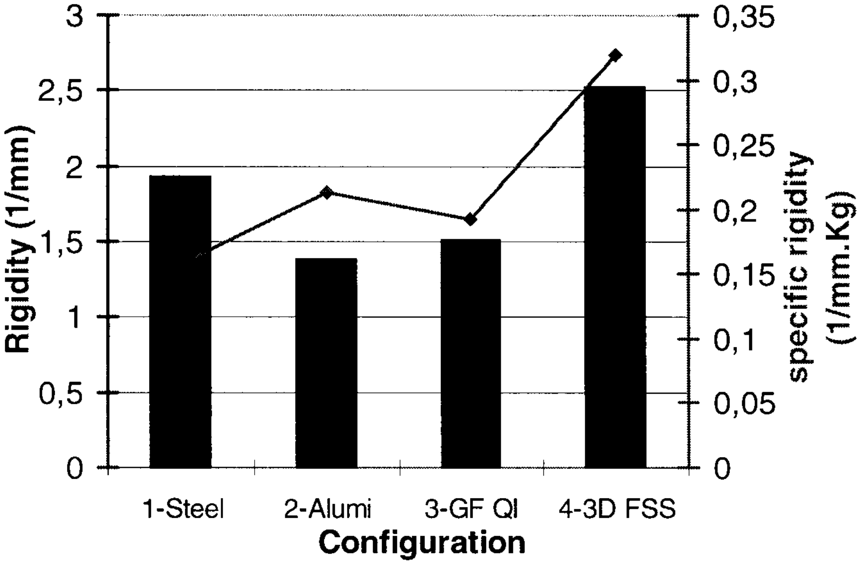


*6* Bending moment load case.

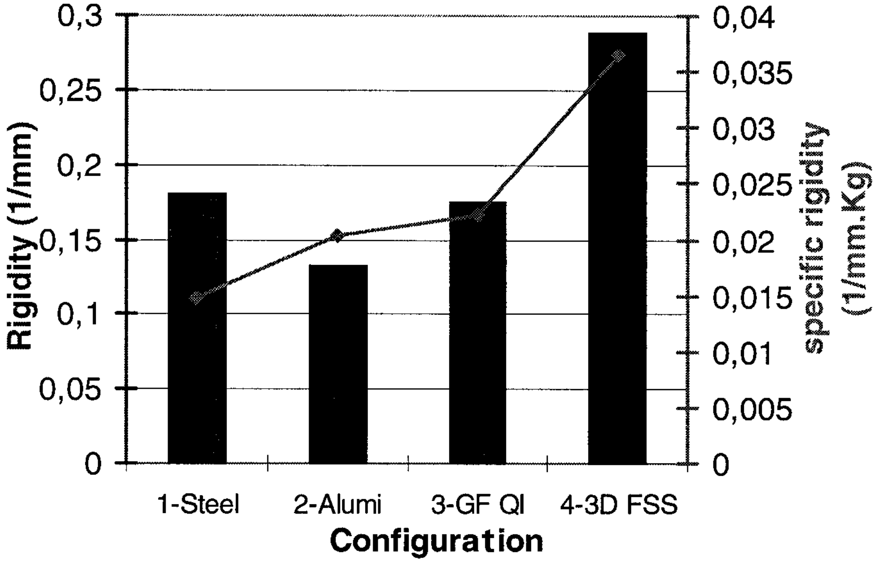
warp knitted sandwich structure, followed by steel, aluminium and quasi-isotropic glass fibre (Fig. 8). In terms of specific rigidity, the optimum material is the warp knitted sandwich structure, followed by the aluminium, quasi-isotropic glass fibre and steel (Fig. 8).



*7* Torsion moment load case.



*8* Rigidity and specific rigidity for the bending case.



*9* Rigidity and specific rigidity for the torsion case.

Finally, for the torsion case, the maximum rigidity was obtained by the warp knitted sandwich structure, followed by steel, quasi-isotropic glass fibre and aluminium (Fig. 9). In terms of specific rigidity, the optimum material is the warp knitted sandwich structure (FSS), followed by the quasi-isotropic glass fibre (GF Q1), aluminium and steel (Fig. 9).

## Conclusions

This introductory chapter has been written in order to clarify why 3-D textile technologies are being used in conjunction with composite materials. It is obvious that the main disadvantages of standard laminated composite materials may be overcome by implementing the 3-D textile technologies available nowadays.

However, methods for predicting mechanical properties of 3-D textile reinforced composite materials tend to be more complex than those for laminated composites because the yarns are not straight. Also, the existence of undulations or crimps in the yarns may reduce some mechanical properties such as tension or compression strengths.

It is clear that further work must be done before the efficiency of this generation of materials for structural applications can be finally assessed. In the following nine chapters, a number of subjects related to this area are studied.