3D-TEXTILE REINFORCEMENT IN COMPOSITES– MECHANICS, MODELLING, PROS AND CONS

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Abstract

Fibre reinforced composite materials are quite rightfully accused of suffering from poor out-of-plane mechanical properties, and delamination concerns are known to strongly reduce their competitiveness in certain types of applications. Several methods have been invented and explored aiming at improving their 3D performance but none of them has yet received broad acceptance and utilisation in practical use. One of the reasons is likely that improved out-of-plane performance by means of through-thickness reinforcement inherently compromises the in-plane performance. The paper predominantly discusses 3D reinforcement from a general point of view but some more specific results from recent work on composites containing 3D-woven fibre reinforcement are also presented. Potential benefits and drawbacks of using 3D textiles in composites are discussed and partly quantified. The trade-offs that become accentuated when introducing 3D reinforcement in composite materials can then be approached through use of more informed design principles.

1 Introduction

1.1 Background

Fibre reinforced polymers is a class of composite materials offering a lot of benefits in lightweight structural applications. Among other things, the fibre reinforcement contributes to the stiffness and strength while the polymer matrix provides toughness and mechanical bridging between the fibres. The fibres can be arranged in a multitude of ways, ranging from virtually random distributions to very sophisticated architectures. Composites materials are in most of their applications utilized as shells structures carrying load predominantly as in-plane tension, compression and/or shear, and under such circumstances in-plane fibre arrangements are both feasible and suitable. However, when shell structures become large and relatively thin their strength in compression typically becomes controlled by structural stability rather than material strength. Buckling becomes an issue, making the bending stiffness crucial for the load-carrying capacity. As countermeasures for preventing buckling shell thicknesses could be increased, monolithic shells could be replaced with sandwich panels, or stiffeners could be introduced to support the shells and reduce buckling wavelengths. Stiffeners are then also typically thin-walled but their geometry is not restricted to a single plane. Different beam profiles, such as e.g. L, T, Z or I shapes are often employed to stiffen shell structures. However, as soon as the 2D orientation of the material and the load is compromised, the out-of-plane strength of the materials becomes an active design parameter too. Since pure shell loading conditions seldom prevail in complex structures and most composite materials contain 2D reinforcement the out-of-plane strength and the tendency for delamination usually comes up as a great concern in design and in-service use of composites.

Introduction of non-plane structural parts also brings about another challenge for composites engineers; how to best design and produce 3D parts from textile reinforcements that typically come as thin 2D sheets. No matter if prepreg tapes, weaves or non-crimp fabrics are used, such prefabricates need to be cut, folded, draped, stacked and joined into some kind of 3D preform before they can finally be consolidated into a single integrated composite part. All such steps involve costs and quality risks in production and, on top of that, the result is often far from optimal when it comes to how the fibres are orientated with respect to the in-service load paths in the part. Junctions between mutually perpendicular sections are always potential sites for damage initiation and growth due to induced out-of-plane stresses. Fig. 1 illustrates a T-section – a very common structural element that is prone to fail due to delamination in the vicinity of the junction. When the poor out-of-plane strength becomes the active design constraint whole parts often become considerably thicker and heavier than required from their primary structural function.

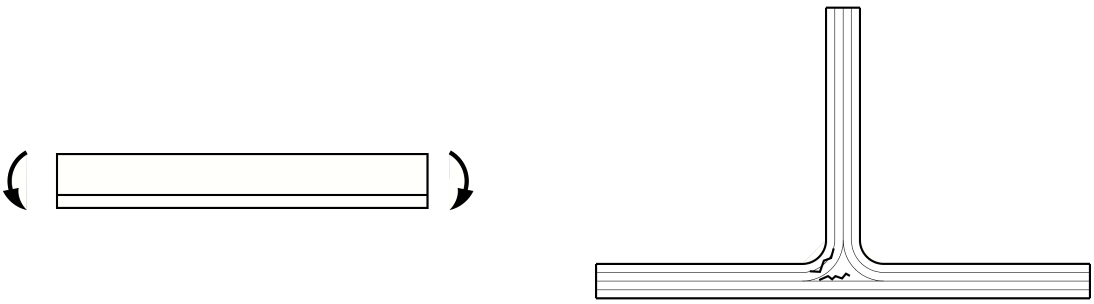


Figure 1. A typical wall junction problem illustrated for a T-section under global bending. Out-of-plane stresses lead to onset and growth of delamination cracks, partly since the orientation of the reinforcement generates unfavourable load paths in the part.

Several innovative methods have been tried to increase the out-of-plane strength of composite materials, such as e.g. stitching, pinning and stapling through the thickness. Attempts have also been made to increase the strength of the matrix material by doping it with various additives and, more recently with e.g. nano particles, fibres or tubes. Regardless the efforts most of the methods suffer from drawbacks making very few of them common in large-scale production. The methods are usually hampered by high cost and/or difficulties to manage consistency and quality assurance in industrial production. They could also bring about other side effects such as poor surface properties, induced stress concentrations or distortion of the in-plane reinforcement.

3D textile reinforcement technologies bring about several potential benefits by offering greater freedom in fibre orientation than conventional 2D reinforcement alternatives, and means to produce more complex fibre preforms through fewer production steps. There exist several 3D textile technologies and products, such as woven, braided, knitted, non-interlaced and combinations thereof, providing more or less of the mentioned benefits, and being suited for broader or narrower ranges of applications. The scope here is however neither to present a complete list of the textile solutions, nor to rank them or argue for the superiority of one or another.

Mouritz et al. [1] provided a thorough review of 3D reinforced composite materials, rich with descriptions and references to various 3D textile and translaminar reinforcement methods.

Bogdanowich and Mohmed [2] more recently provided another review, also rich with references to other relevant papers in the area. A number of benefits and drawbacks with various 3D reinforcement methods are listed in the work and the authors try to distinguish them from what can be referred to as thick 2D materials. They also make a quite rigorous attempt to set a nomenclature for 3D textile architectures (although they appear to be somewhat inconsistent when it comes to applying the definitions they suggest to some of the methods they present). Their paper also addresses the dilemma of achieving better out-of-plane performance without sacrificing too much of the in-plane properties.

1.2 Scope

The scope of this paper is to discuss benefits and drawbacks of 3D reinforcement in composites, and try to quantify some of the results. Modelling and experimental work performed on composite materials reinforced with what Khokar [3] refers to as "true" 3D-woven material is presented and used as a source of data for the discussion.

2 Main benefits of 3D-woven textile reinforcement in composites

There are two main potential benefits with 3D-woven textile reinforcement. The first is related to manufacturing where advanced 3D textile methods can be utilised to produce complex 3D reinforcement preforms, through just one or a few highly automated production steps. The author has worked with a 3D orthogonal weaving method invented and marketed by the company Biteam, which can be used for direct production from plain yarns to a broad range of beam cross section reinforcement preforms in a single production step. Shapes like e.g. L, T, H and Π can been made with different cross sectional dimensions, and various yarn types and fibre content in different parts and orientations of the reinforcement.

The second benefit lies in the mechanical effect of having fibres in three orthogonal directions, providing stiffness and strength in full 3D. The technology also offers a fibre architecture providing more optimal load paths in branched cross sections such as the above mentioned. As can be seen in the schematic illustration of two 3D-woven T-sections outlined in Fig. 2, 3D weaving makes all yarns run straight through the profile and all weft yarns present in the textile are fully interlaced with the warp.

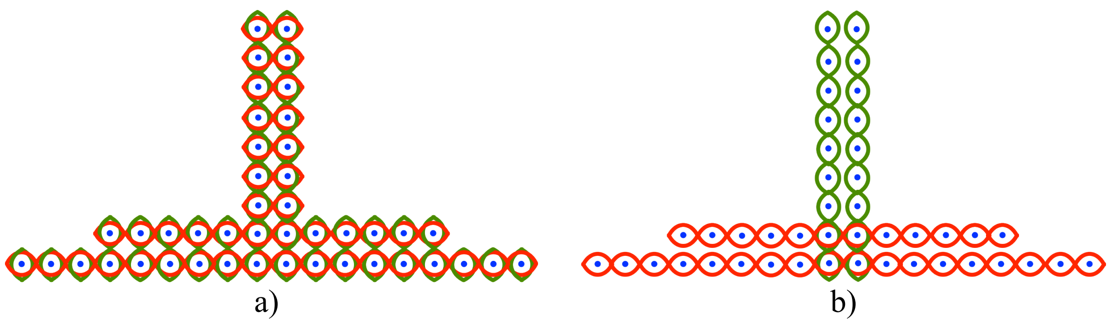


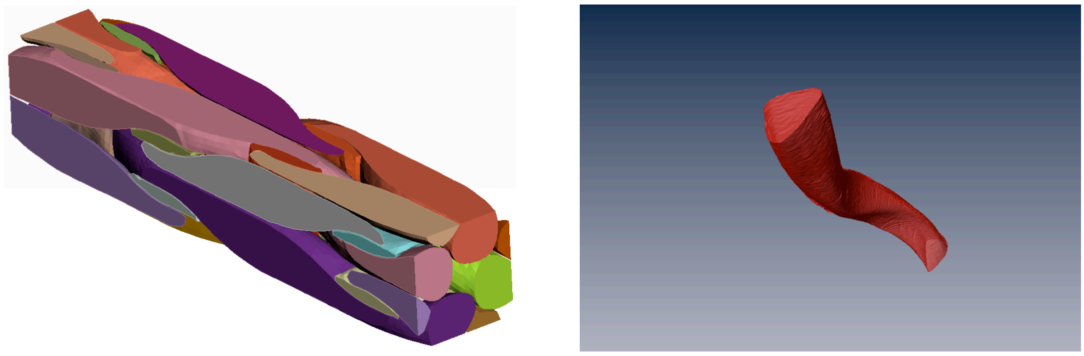
Figure 2. Illustration of a 3D-woven T-sections with warp (blue) horizontal (red) and vertical (green) weft, a) fully 3D-woven, and b) 2D-woven flanges, and 3D-woven junction.

3 Drawbacks with 3D-woven textile reinforcement in composites

From the author's perspective, there are three main disadvantages with 3D reinforcement in composites, one very general and two that are more mechanistic.

3.1 A general problem

Clearly, there exist a multitude of 3D textile reinforcement concepts (and, in addition, several translaminar reinforcement methods for 2D textiles) providing potential for improved performance of composite materials. However, it must be kept in mind that even composites containing only 2D reinforcement, with considerably lower material complexity than 3D textiles, have occupied a field of research for at least half a century. 3D textiles offer yet an order of magnitude (at least) of potential combinations of fibre types, patterns and architectural features, and this fact calls for a certain forbearance. Even for technologies whose potential is not debated, the primarily matter of concern is still the uncertainty of their behaviour and the lack of ability to predict and model it in design. Some of the challenges in modelling are visible in Fig. 3, where a recently developed model of a 3D woven textile [4,5] is displayed together with an X-ray image of an authentic warp yarn.



a) b)

Figure 3. a) An illustration of a periodic representative volume element of a 3D-woven composite, and b) an X-ray image of a single yarn in an authentic material sample.

As can be seen, yarn paths and shapes in the 3D textile are quite intricate and not easy to idealise by simple means. The developed modelling scheme is quite successful in terms of realistic geometric representation of 3D textile architectures, and it enables FE analysis and predictions of homogenised constitutive properties of the composite material. Nevertheless, the current knowledge base and the ability to provide complete material data for e.g. beam profiles like the ones in Fig. 2 is everything but complete.

3.2 Mechanical drawbacks

One mechanical drawback is related to inefficient packing in 3D, affecting the fibre volume fraction negatively, and the other is related to loss of stiffness and strength due to yarn crimp.

2D arrangements of fibres allow for quite efficient packing, with hexagonal close-packing and corresponding fibre volume fraction

$$v_f = \frac{\Pi}{2\sqrt{3}} \approx 0.907 \tag{1}$$

being an upper bound for unidirectional fibre orientation. In laminates with different orientations in different plies some fibre content is lost to resin rich layers between the plies. In theory the reduction of fibre content needs not be more than a local reduction of fibre volume fraction to

$$v_f = \frac{\Pi}{4} \approx 0.785, \tag{2}$$

in interlaminar layers with thickness of the same order as the fibre diameter. In practice both the inter- and intra-ply fibre content is typically considerably lower, typically in the order of 20% lower, than the theoretical limit, corresponding to about 1 μm spacing between individual filaments.

Introducing fibres in a 3rd principal direction induces another kind of packing problem, working at a length scale in the order of the thickness of the fibre bundles in the textile. In principle, the reinforcement in the 3rd principal direction dilutes the fibre content in the two original directions by introducing matrix rich areas in the material architecture. Figure 4 illustrates a schematic representative volume element (RVE) of a 3D textile, in the shape of a prism with dimensions $1\times1\times\beta$. The cross section of the tow of length β is $\alpha\times\alpha$, where $0\le\alpha\le1$. The two remaining tows have cross section areas of equal size, but not necessarily equal to that of the first tow. The RVE is not entirely general but still considered valid for estimating upper bounds of fibre volume fractions for a broad range of 3D textiles. From simple geometric considerations the maximum inter-tow packing in the RVE is then given by $1+\alpha^2-\alpha$, for all $\beta\neq0$.

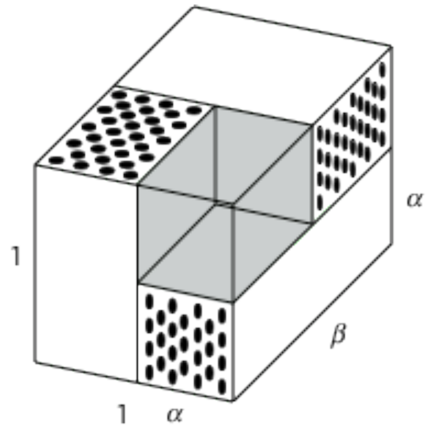


Figure 4. Schematic illustration of the principal packing of fibres in a 3D textile.

Adding the intra-tow packing gives an overall fibre volume fraction as outlined in Fig. 5. It should be noted that the RVE in Fig. 4 is non-interlaced. For a woven architecture the inter-tow packing is even less effective due to tows shifting positions. The side aspect ratios of the different tows then also influence the packing efficiency.

The second negative effect of 3D woven reinforcement is the crimp induced by the interlacement of tows in the textile architecture. Fibre crimp is known to reduce the stiffness of composite materials. Here crimp is defined as the true yarn length within a RVE divided by corresponding RVE side lenth. Figure 6 illustrates some stiffness results as function of crimp, showing that about 50 % of the non-crimp stiffness is lost already when the crimp is equal to about 1.03.

The degradation of tensile/compressive strength due to crimp is of the same order as the stiffness degradation. Yarn waviness is obviously detrimental in compression since it induces buckling of the reinforcement. The main mechanism behind the lost strength in tension is that fibre crimp induces shear stresses in the matrix material when tensile loads are applied. The material then typically exhibits premature failure initiation at global strain levels similar to those in compression. The ultimate tensile load is often much higher than the load at on-set of failure but that is of lesser practical interest.

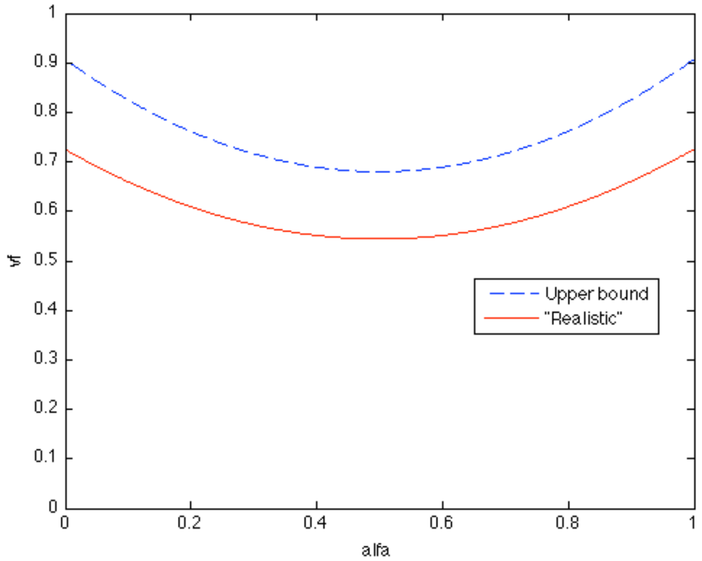


Figure 5. Fibre volume fraction of the RVE in Fig. 4 – upper bound and more realistic (80%).

Some of the estimates provided in this section are rather simplistic but still quite representative. They are predominantly conservative and believed to be reasonably general and valid for a broad range of 3D textile reinforcements.

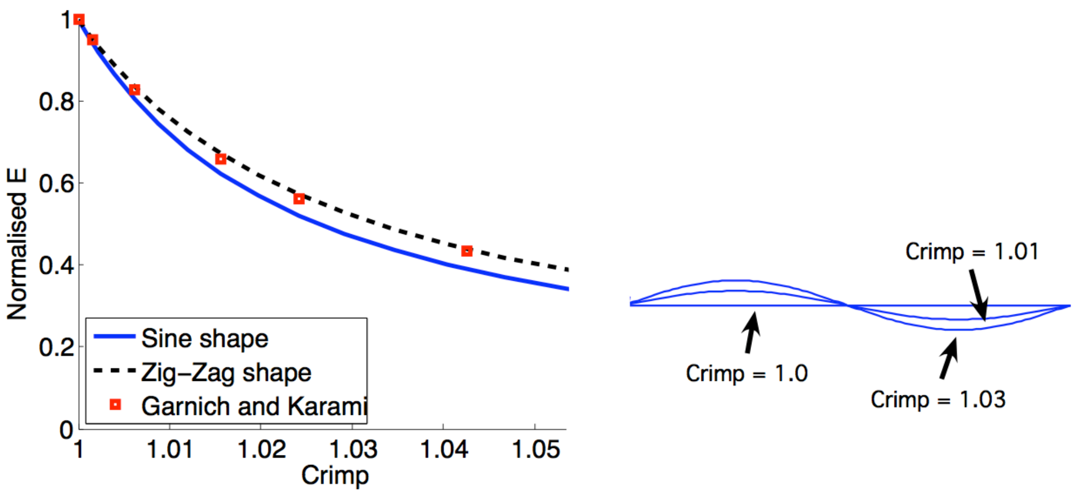


Figure 6. Effect from fibre crimp on the stiffness of composite materials, from [6] and [7].

4 The trade-off dilemma

First of all we need to revisit the reasons for using composite materials in the first place, using aircraft structures as an example. Prepreg-based carbon reinforced epoxy is about 40-45% stiffer and stronger per unit weight than Aluminium. The effect on the bending stiffness is even greater since the higher thickness of a composite panel with equivalent in-plane stiffness as some reference Al panel contributes to the bending stiffness with at least a factor of 2. It is, however, obvious from the crimp results above that virtually all of the weight-competitiveness of the composite material concept is lost if the reinforcement is woven. Woven reinforcement also brings about resin-rich pockets in the material structure, which are likely to have a negative effect on the fatigue life. The fact that unidirectional prepreg tapes and non-crimp fabrics are favoured in high-performance composite applications is thus not without reason.

Secondly, it appears like very little through-thickness reinforcement is sufficient to eliminate delamination problems. Ongoing work as well as results from literature indicate that as little as a few percent appear to improve the out-of-plane strength and fracture toughness dramatically. Furthermore, the lesser through-thickness reinforcement the lesser induced crimp in the in-plane reinforcement, and the lesser reduction of overall fibre volume fraction in the material.

Final remarks

3D reinforcement enables production of composite materials with significantly better out-of-plane performance than their 2D reinforced counterparts. An even greater benefit is the ability to produce complex three-dimensional fibre preforms to net shape using a single or just a few highly automated production steps. There are also several drawbacks with 3D reinforcement such as loss of in-plane mechanical properties due to considerably reduced fibre volume fraction and induced crimp. A condition for 3D reinforcement methods truly breaking through as competitive alternatives to conventional reinforcement concepts is that some of their drawbacks are suppressed. Ideally, non-crimp fibre architectures should be combined with yarn interlacement at junctions, e.g. as outlined in Fig. 7, in order to fully utilise the benefits of different reinforcement principles by using them where they best contribute to desired mechanical performance.

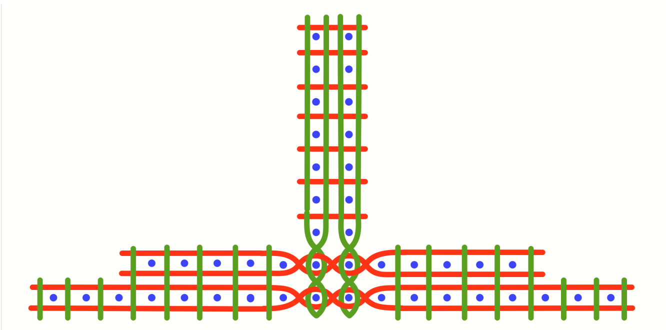


Figure 7. A fictive textile architecture combining benefits of different reinforcement principles at different locations of the beam profile.

In addition it is desired to have fibres not only in three orthogonal directions but also in bias angles between the principal axes, allowing for tailoring of the reinforcement with respect to the anticipated load paths in the composite structures.

Last but not least, engineers in industry need to be supported with adequate design methods, tools for prediction of material properties, and failure criteria, in order to make the material concepts truly available to the engineering community.

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