An Overview On Development Of Three Dimensional Reinforcements For Use In Composites At CSIR-NAL

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***Abstract*— 3D composites have potential applications in aerospace, space and defence sectors. Skin- stiffener elements in wings, aircraft and spacecraft root fittings, armors, helmets & bullet proof vests, engine components such as nozzles, exhaust cones, convergent-divergent flaps, etc.. are the potential areas of interest for 3D composites. These composites have the ability to improve the out-of-plane properties which has been one of the challenges currently faced by composite designers. The interweaves of the 3D reinforcements in the composite will hold the structure together when subjected to thermal shocks and exposure to high temperatures. Also, it has been shown that the stress analysis conducted on a 3D composite has isotropic thermo-mechanical loading regime. This paper details about the development of 3D weaving technologies for use in composites keeping the above applications in hindsight. The focus of the work is on single layer profile weaving for inserts, angle interlock and noobing technologies for integrated thick structures and 3D weaving technology based on dual-direction shedding principle for integrated thick profiles used in fittings.**
Keywords—3D weaving; Noobing; Rocket nozzles; Thermal protection systems

Nomenclature & definitions:
Noobing : Non-interlaced 3D weaving
Preform : A combination of 2D and/or 3D reinforcement technologies combined to develop the required end-product
Warp (X) : Longitudinal threads used during weaving for cloth formation
Weft (Y): Transverse threads used during weaving for cloth formation
Z threads : Vertical threads or binder threads
Let-off : letting off of X threads in an incremental manner required for weaving.
Shedding : Means of separation of X threads using suitable devices for insertion of Y or Z threads
Picking : Insertion of Y or Z threads using suitable device in the separated X threads
Beat-up : pushing the just inserted weft to the cloth formation edge called fell using a suitable device
Take-up : Winding of cloth onto cloth beam or laying on suitable flat device.
Roving : Bunch of untwisted filaments
Tex : Designation for thread count (weight in gms per 1000 mtr length of the yarn)
Tappet/Dobby / Jacquard looms : Types of looms
Picking : Insertion of transverse threads by suitable mechanism
Beat-up : Moving the previously inserted weft to the cloth formation edge called fell
Take-up : Taking up of the cloth onto the cloth roller
Interlacement pattern : The manner in which the warp and weft interweave
Weave design plan : comprises of design, drawing-in-order, lifting plan and denting order of requirement to the weaver to weave the structure on the loom
Tex : Weight in grams of the yarn for a length of 1000 mtrs.
Thread density : Yarn spacing per unit length of the fabric

I. INTRODUCTION

The primary focus of technology development aims at meeting the performance requirements using the most ideal solutions. The critical requirements that need to be met becomes the driving force in most of the cases. In the case of structures used in aerospace, space and defence sectors, weight saving is one such critical requirement as it will have a cascading effect of saving fuel, improved performance, increased payload etc., To a major extent, today, composites are used extensively to take advantage of their weight saving potential in addition to meeting the performance requirements of the component in question. However, as is the case with any technology, a few drawbacks do exist with composites. Composites being layered structures, delamination, poor out-of-plane strengths, poor impact damage tolerance etc., are some of the issues that are required to be addressed to expand their scope of application. The above issues can be addressed using the technology of 3D reinforcements. This paper details about the efforts being put at CSIR-NAL to develop, indigenize and utilize the 3D reinforcement technologies for the benefit of the composite community.

Fig 1 below details about a simple classification of 3D reinforcements for prospective use in composites.

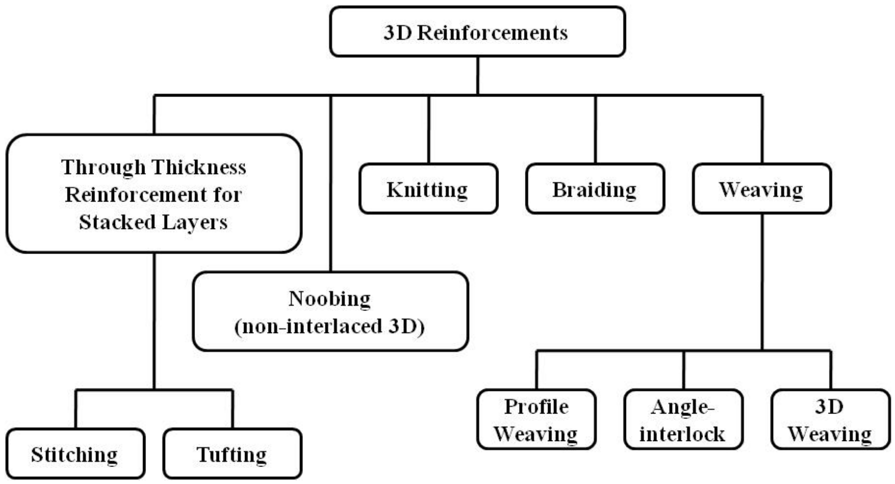


Fig 1: Broad classification of 3D reinforcements

Developments at CSIR-NAL are focused on single layer Profile weaving, Noobing, Angle interlock weaving and 3D weaving based on dual direction shedding approach. Single layer profile weaving, Noobing and angle interlock weaving are carried out on a custom designed computer controlled 2D weaving machine. For 3D weaving based on dual direction shedding approach, a prototype machine based on original concepts is being built at CSIR-NAL under a funded programme.

II. Machinery for 3D Reinforcements

The main requirement of 3D reinforcement development will be custom designed machinery. Specific type of 3D reinforcement calls for specific type of machinery. Existing .2D looms can be modified to develop 3D reinforcements examples being in the area of Noobing, Angle interlock weaving. Fig 2 shows the line diagram and the photograph of a custom designed 3D weaving machine at CSIR-NAL for weaving single layer profiles, noobed and angle interlock structures. The unique features of the machine is that, it consists of multiple warp beams to feed multiple warp layers, Positive take-up for ensured weft delivery, multi beat-up action for firm and compact beat-up, Take-up at will for obtaining thick performs, stacking of multiple numbers of Y threads at the fell to meet the required preform thickness & ensuring that the preform developed is as per the designed weave architecture (especially Z yarns). Few of the warp beams cater to the Z thread requirement to make the 3D Structure. 3 types of 3D preforms viz., Single layer profies, Noobed structures, Angle interlock structures were woven using the machine. The following sections discusses about the above developments.

III. Single layer profiles

Single layer profile weaving is the simplest 3D reinforcement that is in vogue in the textile industry as it can be woven on the existing commercial 2D weaving machinery with very minor modifications. Dale Abidaskov et al.,[1] have patented the profile weaving of ‘H’, ‘Y’ and ‘Pi’ which are used as connectors in structural components. Walter[2] has woven a double ‘I’ beam using Nylon for applications in internal conduits. Ronald Schimdt et al.,[3] have patented the profile weaving of multi-layer ‘T’, ‘π’ and ‘+’ based on the concept of single layer weaving principle.

In a novel approach at CSIR-NAL, as a via-media solution to improving the strength of T joints used in aircraft wings, single layer T’ inserts (Fig 3) were woven in the shape of a folded ‘T’ incorporating the noodle region in the weave architecture based on the concept of double cloth construction. Three types of inserts using 3K and 6K of TC-

33 medium modulus grade carbon tows were evaluated. The inserts were incorporated in the T joint construction as shown in Fig 6. Composites prepared using Vacuum Enhanced Resin Infusion Technology[4] showed improved load carrying ability (Fig 4) [5] due to the ability of the insert to bridge the three sections of the T joint, thereby retarding the failure process. These inserts can be woven in large quantities and can be easily incorporated into structures where feasible. They also have good prospects to meet the qualification requirements (when used in aircraft, spacecraft applications), hence making them commercially viable.

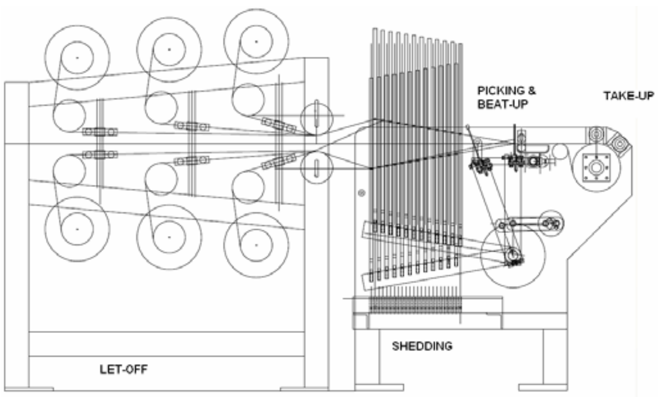


Fig 2 : Line diagram and photograph of multi-beam 3D weaving machine

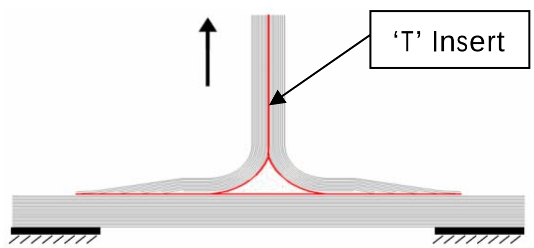



Fig 3 : Photograph of 'T' insert & its inclusion in T Joint construction [5]

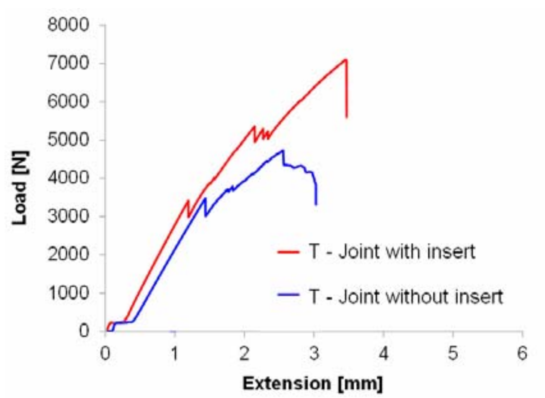


Fig 4 : Test result of composite T joints with & without Insert [5]

IV. NOOBING

NOOBED[6] structures is an acronym for Non-interlacing, Orthogonally Orientating and Binding. Noobing is defined as the process of producing 3D fabric by non-interlacing, orienting orthogonally the three sets of yarns and integrating the structure through binding. Noobed structures can be Uniaxial, where the yarns are Orthogonally positioned in X, Y & Z directions or multiaxial which includes additional set of yarns in ±θ° direction as shown in Fig 5.

Fig 6 shows the weave architecture of a uniaxial noobded structure with 5 weft layers and 8 warp layers woven to a thickness of about 2 mm. As can be seen from the architecture the binder yarns splits into the Z component and part of the X component (X_2). The stuffer yarn becomes the X_1 component. The dots in the figure are the Y content yarns. The fibre weight content and other preform evaluation details are shown in Table 1. As can be seen from the weave architecture, there is possibility of tailoring the X, Y & Z content. Possibility exists for increasing the fibre volume content by increasing either the Tex of the yarn or the thread density. The primary advantage of a noobed preform is that the yarns are uncrimped and their paths are nearly orthogonal to each other. It will cater to the needs of the components with multidirectional stress scenarios. Typical application would be wing-root-fittings of aircrafts.

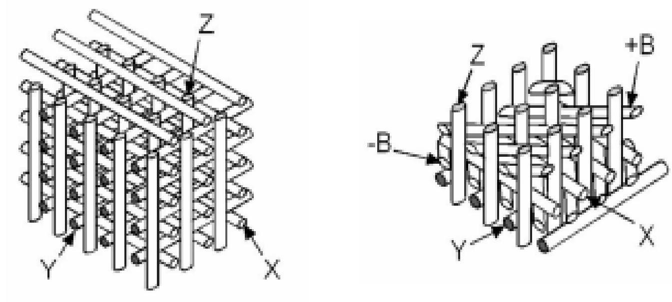


Fig 5 : Uniaxial and Multiaxial noobed structure [6]

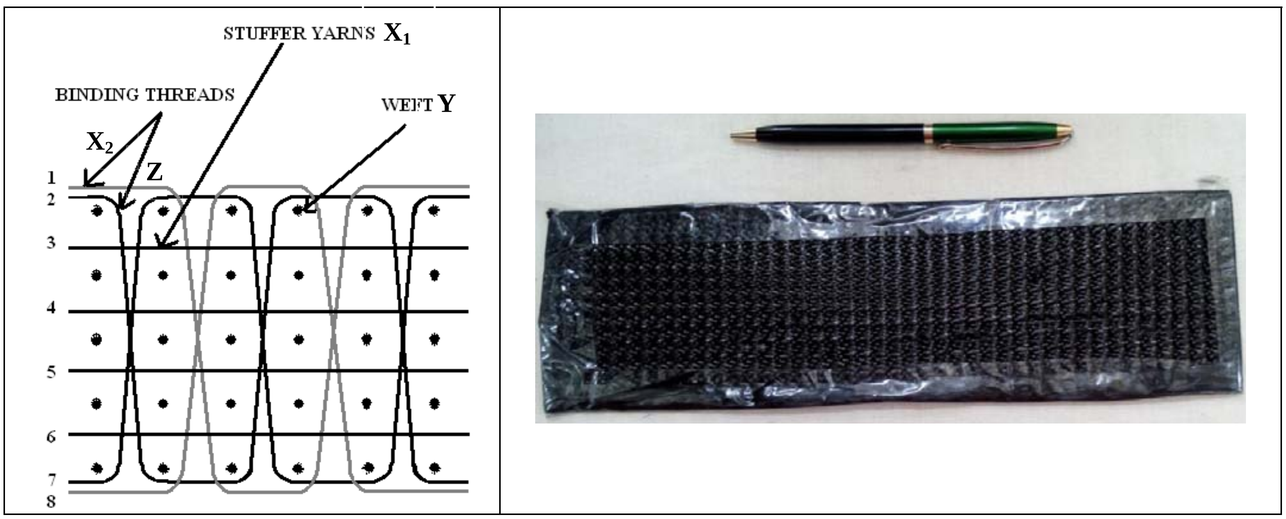


Fig 6: NOOBED architecture and sample woven

TABLE 1: DETAILS OF NOOBED PREFORM

Thickness(cm)	0.176
Stuffer warp density (X1)(per cm)	6.3
Binder warp Density (X2, Z)(per cm)	6.3
Weft density (Y) (per cm)	15.7
Z thread density (per cm)	1.58
Fabric volume content (%)	39.1
Warp content (X) (%)	41.9
Weft content (Y) (%)	52.3
Z content (%)	5.8

V. ANGLE INTERLOCK WEAVING

Angle interlock weaving in its simplest definition is about interlacing several layers of warp with several layers of weft to form one integrated bulk preform. The Z threads here are oriented at an angle as a result of the unique weave architecture. The surface of the angle interlock preform is characterized by wave patterns representative of the weave architecture. Fig 7 shows the weave architecture of a typical angle interlock structure and the surface wave pattern in a angle interlock preform woven using carbon tows at CSIR-NAL. Composites made out of these preforms have exhibited improved shear and flexural properties. The complex weave patterns are good candidates for impact damage tolerance. The basic architecture being tailorable, thin angle interlock preforms have the ability to take up complex contours of moulds as is the case with fan blades[7]. Angle interlock woven structures, due to the network of interweaves are good candidate materials for damage tolerance as well as high temperature applications

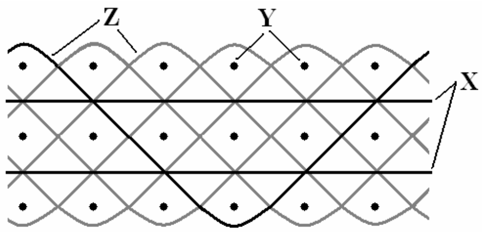


Fig 7: Line diagram of Angle interlock weave pattern and the characteristic wave pattern of the woven surface

VI. 3D WEAVING BASED ON DUAL DIRECTION SHEDDING

Three dimensional weaving based on dual direction shedding[8] is a very specific technology for composite profiles and joints. In simple terms, it is about weaving the cloth in three dimensions with orthogonal yarn interlacements in X, Y and Z directions. The working principle of 3D weaving is similar to 2D weaving with the primary motions of shedding, picking, beat-up and secondary motions of let-off, take up required to be carried out in both the horizontal and vertical planes. The complete weaving cycle is detailed in Fig 8. Figs 8a shows the grid like warp arrangement. Figs 8b to 8g shows half the weaving cycle and Figs 8h to 8m shows the other half of the weaving cycle required for the completion of 3D weaving. Fig 8n shows the cross-section of the 3D woven preform. Here weft insertion will be positive (aided shuttle transfer) & simultaneous in a given plane for all the layers. Beat-up is required to be carried out for each plane. Take-up will be linear and as per the type of profile being woven. Specific warp arrangement will be required for specific profiles (Fig 9). Three broad types of profiles viz.,. Single stage profiles (Fig 9a), Two-stage profiles (Fig 9b) and generic profiles (Fig 9c) can be woven using this technology. This technology is similar to noobing, the main difference being the interlacements. When a block noobed preform is cut, the threads unravel as the binding there, is only at the edges, whereas a 3D woven block preform behaves like a cloth when cut as the interlacements hold the uncut portions together. These structures are very good damage tolerant materials for specific applications and have the potential to simplify the design of joints in composite structures.

PROSPECTS AND CHALLENGES

3D reinforcement technologies have promising roles to play in wide variety of applications[9] but cannot provide off-the shelf solutions. As is the opinion of several researchers, each prospective application to incorporate 3D reinforcements, requires to be looked into, in entirety instead of a simple part replacement, as is usually done in most of the cases. Marshall and Cox[10] are of the opinion that incorporation of 3D reinforcements requires redesigning of the component and sometimes even the surrounding structure and the manner in which they could be coupled. Potluri[11] is of the opinion that use of 3D technologies requires a means of bias yarn introduction as some of the applications require interlacement of non-orthogonal yarns and the requirement to create local features in the component.

VII. 3D TEXTILES FOR SPACE ENVIRONMENT

Specific to space environment, 3D reinforcements can play a revolutionary role to meet the structural and thermal requirements of the spacecraft and its components. On the structural front possibilities exist for 3D reinforcements to be used in joints, stiffener elements, attainment of structurally robust thin skins (less than 1 mm)[10]. Tennyson & Lamo have detailed upon[12] hypervelocity impact conditions that are most likely to occur on space craft in low earth orbit (LEO, 200 - 1000 Km altitude). Here the components currently made of PMC's (antenna struts, panels and low distortion frames) are vulnerable to impact damage resulting from collisions with natural micrometeoroids (dia < 1 cm) and orbital debris (known as the MOD environment). 3D reinforcements can be considered for the MOD environment.

On the thermal front, 3D fibre reinforcements enable compliant integral attachments that avoid thermal stress build-up, thin interwoven skins that can sustain through thickness thermal gradients (>1500°C mm^{-1}), embedment of alloy struts in the weave to enable joining a hot ceramic skin to other structures such as a structurally efficient truss sub-structure while protecting the skin from thermal stresses[13,14]. Representative Rocket nozzles, thermal protection systems and hypersonic flow path components have been demonstrated successfully using 3D reinforcement technologies.[15,16]

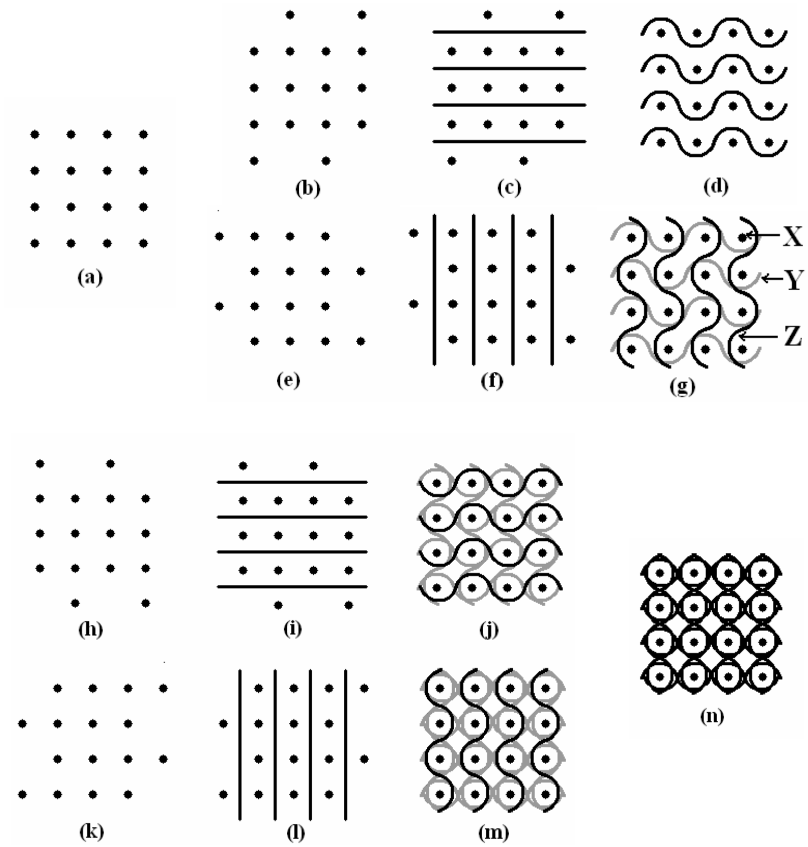
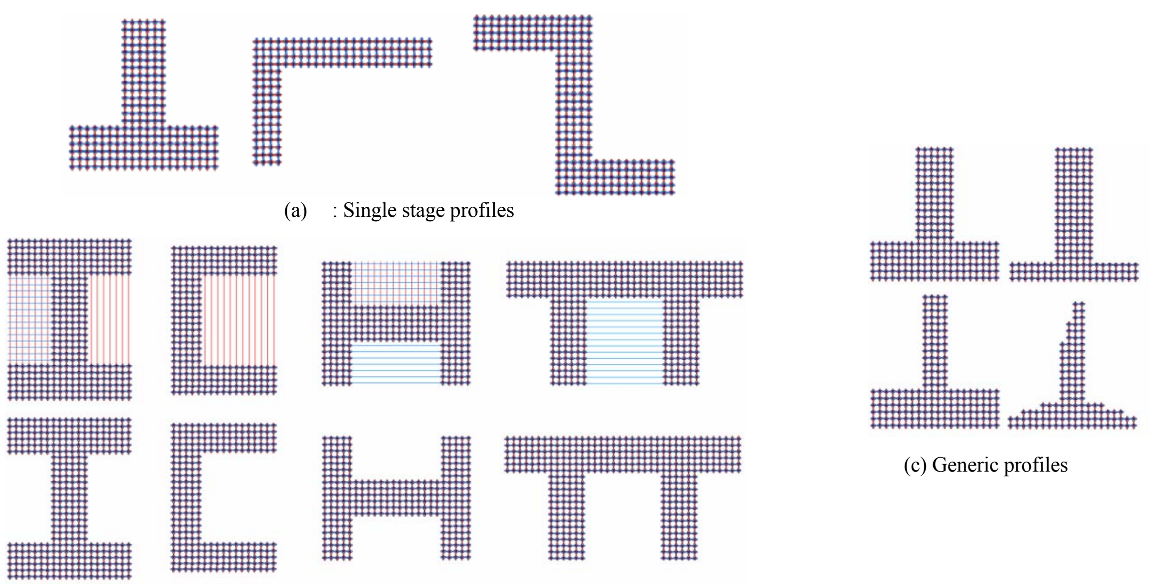


Fig 8 : 3D dual direction shedding weaving approach; (a) Grid like warp arrangement (Neutral position); (b)Vertical shedding; (c) Horizontal pick insertion; (d) Neutral position; (e) Horizontal shedding; (f) Vertical weft insertion; (g) Neutral position & completion of half weaving cycle; (h) vertical shedding; (i) Horizontal weft insertion; (j) Neutral position; (k) Horizontal shedding; (k) Vertical pick insertion; (m) Neutral position and completion of full weaving cycle; (n) 3D woven preform.



(a) : Single stage profiles

(c) Generic profiles

(b) Two stage profiles

Fig 9: Possible profiles by 3D weaving

VIII. SUMMARY

3D reinforcement technologies have promising application potential in wide spectrum of fields ranging from niche areas of aerospace, space & defence to the commercial arena of automobiles, clothing sector, interior designing etc., In the space environment the technology can cater to the need of structural and thermal requirements. Typical solutions have been provided for rocket nozzles, thermal protection systems and hypersonic flow paths.

This article's focus has been about the development and indigenization efforts of the variants of 3D technologies at CSIR-NAL. The technologies chosen above (single layer profile weaving, noobing, angle interlock weaving and 3D weaving) have various degrees of complexities, potential & challenges. The choice of these variants has been done keeping in view the requirement of composite structures where noticeable improvement in performance is expected ex., T stiffeners, Thermally stressed components. Specific application of 3D technology, calls for renewed view from the design angle, possible development of specific infrastructure and evaluation to meet the qualification requirements as it cannot be a simple part substitution.

In a nutshell, while 3D technologies cannot provide off the shelf solutions, they have the potential to revolutionise, simplify and make a land-mark contribution to the design and development of composite structures.

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