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REVIEWS

# 3D Composites: Opportunities & Challenges

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**Abstract |** 3D composites are creating a furore among the composites community, especially the aeronautics, space and defense sectors. Literature reports on 3D composites discuss a wide spectrum of 3D technologies encompassing weaving, stitching, braiding, tufting etc., that are at various stages of development and implementation. Choice of technology for a particular end use is based on various factors such as need, problem to be addressed, expected performance requirement, practicality of development and the like. Two broad areas of application for 3D composites are in the structural and thermal segments. Opportunities for 3D composites exist in the form of performance improvements for components having multidirectional stress states, simplified & radically different designs, reduced part count and reduced labor cost. Challenges that need to be addressed include achieving a balance between in-plane & out-of-plane properties, processing issues for thick & compact 3D structures, out-of-plane testing approaches and integration challenges with metal/2D composites. This paper reviews the current status and looks at what the future has to offer for this upcoming technology.

## 1 Introduction

Development of 3D composites is a '*technology by itself*', comprising 3D reinforcements and suitable matrix material similar to 2D composites. However, reinforcements make the difference between a 2D and 3D composite. In a 2D composite, the reinforcement comprises yarns in X & Y directions interlaced in one of the various textile process of weaving (most popular), knitting or braiding, whereas 3D reinforcements for composites comprise yarns in X, Y & Z directions. While, there are established processes in the textile industry to develop 2D reinforcements, 3D reinforcements, being a lot-more complex, are yet to make their mark in entirety. Several variants of 3D technologies exist—Stitching, Tufting & Z pinning technologies are simpler, and are the via-media approaches to developing 3D reinforcements. With advances in robotics, these technologies are commercially viable today and feasible for varied types of components and structures. On the flip side, they cause damage to in-plane fibres, resulting in reduction of in-plane properties. The other technologies such as noobing, knitting, braiding and weaving create the 3D preform based on the particular textile process. These processes invariably call for custom designing of machines in most of the cases, and to a reasonable extent can be developed on modified 2D weaving machines. Some specific cases require machines to be built entirely on new concepts with marginal contribution from the 2D textile machinery line. With this backdrop, this paper reviews the developments in the 3D composites sector and envisages future potential for this upcoming technology.

At the outset, several versions are cited for classification of 3D reinforcements. 2D and 3D fabrics are demarcated by simply considering the placement of yarns in each plane along with defining and classification of noobed structures as uniaxial and multiaxial.[1] Another classification on 3D reinforcements detail the history and application of 3D composite structures, and classifies 3D reinforcements based on woven and non-woven categories with emphasis on fiber orientation.[2] Yet another approach[3] gives a vast description of 3D reinforcements, classifying

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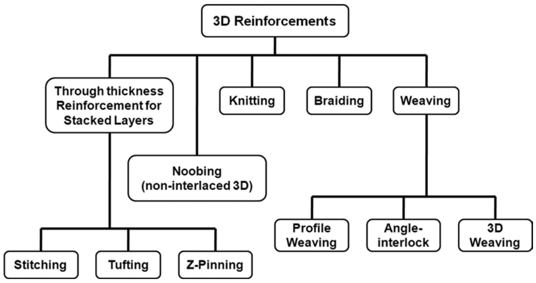


***Figure 1:*** Simple classification of 3D reinforcements.

3D orthogonal structures as 3D solid structures. Consolidating these and similar other works, a simple classification is shown in Figure 1, wherein the spectrum of work being currently carried out on 3D composites falls under one of the categories. The most popular developments have been in the area of through thickness reinforcements for stacked layers, noobing and weaving technologies; this paper focuses on the developments in these areas. The complexity of yarn architecture in knitting and braiding has limited their applications in composites.

## 2 Composites with Through-Thickness Reinforcement for Stacked Layers

Stitching, tufting and Z pinning technologies can be considered as 'via-media' 3D technologies, wherein the third direction reinforcement is inserted into the 2D reinforcement block. The stitching process uses two needles on the same side (or either side) of the preform block to insert through thickness threads and lock it, thus providing a through thickness reinforcement. The tufting process involves the insertion of a thread needle into a loose dry fabric or binder preform and its removal from the fabric along the same trajectory The tuft of the thread relies on friction from the fabric itself or hold provided by underlying auxiliary material.[4–6] The advantage of tufting is the low tension under which the thread is inserted resulting in a reduction of the stitching effect on the in-plane properties of polymer matrix composites.[7] Z pinning is the insertion of rigid cured carbon fibres/BMI pins (Z-pins) into the laid up uncured plies, effectively nailing the different plies together. A double layer carrier foam supports and prevents the pins from buckling during the insertion process. The Z pins are pushed through the thickness of the lay-up using a specially designed ultrasonic machine. The excess pin length is trimmed and the collapsed foam is then removed.

Stitching is being considered in the industry for improving the damage resistance/tolerance of composites.[8] Several stitching parameters such as stitching density, thread type, stitch type, needle size/type, thread tension and sewing machine type[9] need to be considered. Studies on low velocity and ballistic resistance of stitched carbon/epoxy laminate. (T-300 tows, Ly 556 resin system) has shown reduction of tensile strength of about 20–25%, but has also shown improvement in compression after impact (CAI) strength.[10] Other studies have shown reduction of 10–20% in stiffness, strength and fatigue resistance.[11] Choice of stitching thread influences the properties of the resulting laminate.[12,13] Stitches[14] do not improve the static strength of joints but significantly extended the crack propagation phase under fatigue loading and are expected to have high in-plane shear properties.[15] It has been shown that the stiffness of the stitching thread has an influence on the damage tolerance capability.[16] Some reports on innovative approach of stitching using low melting temperature yarns[17] have demonstrated feasible way of utilizing stitching technologies for the future automated manufacture of textile performs with improved mechanical properties. Effects of stitching on thermoplastic composites[18] have reiterated the contribution to the crack propagation phase in addition to the influence of impact behavior. Studies have been carried out on size and shape characterization of resin rich regions,[19] new cracking phenomenon,[20] distortion of fibres during stitching,[21] failure mode studies such as shear fracture arrested by stitching threads,[22] and influence on mechanical properties.[23]

Reports on tufting have shown improved mechanical performance under bending stresses with significant strength increase in 3 point bend tests,[24] crack front stoppage similar to stitching,[25] significant increase in joint pull off resistance,[26] increase in CAI strength of 25 to 27% for carbon and glass threads coupled with reduction in tensile strength by 10% and reduction in stiffness by 5% over untufted specimens.[27] Other studies on tufted composites have shown reduction of 10–15% in tensile strength, tensile modulus, compressive strength and compressive modulus with parallel improvement to the tune of 15% in shear, cyclic tensile and compressive strengths[28] and increased delamination resistance.[29]

The crack front stoppage behavior is typical of through thickness materials[30] including the Z fibre insertion.[31] Transiting from stitching to tufting to Z pinning, the rationale has been to retain the in-plane properties to the maximum (to the tune of 98%[32]) while improving upon the specific properties such as mode I fracture toughness, delamination resistance,[33] compression after impact resistance[34] and delamination fatigue crack growth.[35] Studies are ongoing in the direction of stress distributions,[36] required volume content, manufacturing simplicity[37] etc. The fatigue lives of stitched and Z-pinned composites decrease with increasing amount of through thickness reinforcement.[38,39]

Summarizing, 3D composites with through thickness reinforcement for stacked layers cater to the requirement of complex structures, wherein out-of-plane properties are required in local zones such as joints in aircraft wings. Advantages lie in using portable through thickness reinforcement mechanisms for complex parts, undisturbed lay-up sequence thus meeting the design requirements. 3D solutions for complex shaped components utilizing advanced robotics etc. However, some loss in of in-plane properties, lack of product consistency, complexities for product certification exist as of today.

## 3 Weaving Technologies

The most widely used reinforcements for composites are bi-directionally woven, and perform in various forms. Few technologies in the 3D reinforcement sector consider this base of 2D weaving as a stable platform for the development of 3D reinforcements due to commercial viability, versatility, and the ability to be woven on existing textile looms. Single layer profile weaving, angle interlock weaving & 3D weaving[40] based on dual direction shedding approach come under this platform. Few researchers[41] consider the profile weaving & angle interlock weaving as 2D woven 3D fabrics, while 3D weaving[42] is considered as true 3D viz., 3D woven 3D fabric. Noobing,[43] however, is treated as a separate class since it does not have any interlacements between the X, Y and Z yarns, but are bound together at the edges. Manufacture of 3D preforms by weaving is technically more challenging as compared to the conventional cloth formation,[44] particularly if complex geometries are to be realised.[45]

Single layer profile weaving for composites 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. Profile weaving of 'H', 'Y' and 'Pi' has been demonstrated and used as connectors in structural components.[46] Woven double 'I' beam[47] using nylon for applications in internal conduits and profile weaving of multi-layer 'T', 'π' and '+' based on the concept of single layer weaving principle[48] are some of the other details available in literature. Composite properties evaluation reported for a 'T' stiffener, with inclusion of 'T' inserts with woven fillet[49] has shown strength improvement to the tune of 30% with changes in crack propagation modes.[50] While ease of development and commercial viability exists for this technology, it is limited to just single layer with provisions to vary the thickness to a limited extent by using yarns of higher Tex.

NOOBED[51] structures (acronym for Non-interlacing, Orthogonally Orientating and Binding) 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. It is alternately termed as 3D orthogonal structures. It is one of the most popular 3D technologies, and is being extensively explored around the world. Noobed structures can be uniaxial, where the yarns are orthogonally positioned in X, Y and Z directions or are multiaxial, which include additional set of yarns in ±θ° direction, as shown in Figure 2. The primary advantage of a noobed preform is that the yarns are uncrimped and their paths are nearly orthogonal to each other. Several approaches exist for the development of Noobed preforms. Typical application would be structural components with multidirectional stress scenarios.

Weaving of Noobed preforms on 2D machinery result in greater reduction of strength compared to modulus, which needs to be considered during design.[52] Several problems including lack of consistency and low quality have been reported.[53] Therefore, it is customary to develop specific machines. In-plane properties, viz. tensile, compression, flexural properties are 10–20% lower for equivalent in-plane fibre content,[54] attributable to crimping & misalignment of the load bearing fibres caused by insertion of Z binder yarns.[55] The advantages of 3D structures lie in the ability of structure to sustain large strains to failure in compression with improvement of flexural strength[56] and interlaminar shear strength.[57] However, degradation in tensile strength[58] due to crimp added to the structure by the binder tows, shearing of binder tow during entry & exit,[59] resin rich areas due to the presence of binder tows,[60] reduction in

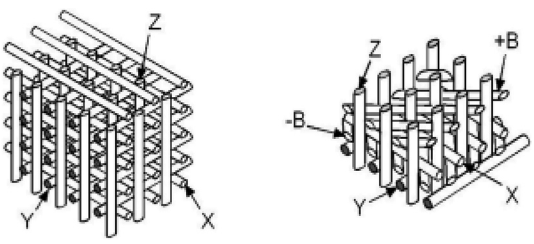


***Figure 2:*** Uniaxial and multiaxial noobed structure.

in-plane tensile fatigue properties due to transverse cracking of resin rich zones with complex fatigue damage mechanisms[61] have been observed. These composites allow the tailoring of properties for specific applications and show better delamination resistance and damage tolerance[62] especially in the thickness direction.[63] Theoretical analysis of the dynamic response of composite T beams[64] carried out using split Hopkinson pressure bar matched well with the experimental data.[65] Comparisons of mechanical properties with equivalent 2D composites have shown higher ultimate stress and strain values especially in 45° bias loading, but the damage initiation threshold is lower.[66] Existence of straight yarns imparts maximum tensile stiffness and strength properties in the resulting composite.[67] Careful control of the tension of the binder yarns contribute to superior tensile properties.[68] Studies on 3D woven CFRP[69] orthogonal composites have indicated complex & rugged fracture paths. The characteristic feature of noobed composites is that the 'through thickness' yarns prevent delamination growth and the interlacing loops link yarns and provide an integrated structure.[70] The loops also hold axial yarns resisting compressive loads, and thereby, the materials are less likely to fail in brittle and catastrophic manner. After the material is damaged, the loops hold the damaged axial bundles, thus making it possible to retain maximum structural integrity. However, the drawback is that they have a role to play in axial yarn deformation, thus lowering the critical stress for fibre micro buckling.[71] Stress-strain relations show significant nonlinearity with the onset and development of damage.[72] Studies for high temperature applications have reported improved impact due to constraining of delaminations in Sic/Sic composite.[73] Several other studies in this direction include stress/strain characteristics[74] fracture behavior at high temperatures.[75] tensile creep characteristics including matrix cracking[76,77] and thermal response.[78] Low velocity impact tests on 3D SiC/SiC show localized damage zones and almost unchanged tensile strength.[79] Studies on E-glass-vinyl ester 3D woven non-crimp fabric composites have shown that about 2% of Z fibre weight content is sufficient to suppress delamination.[80,81] Textile architecture influences on damage accumulation and delamination resistance studied using End Notch Flexure showed localized delaminations, implying prevention of crack propagation from a pre-existing notch[82] which also corroborated with analytical modelling.[83] At high impact velocities, delaminations continue to be the predominant damage mode, although the Z yarns assist in reducing it.[84] Formability studies have shown higher out-of-plane stiffness compared to 2D textiles thus bringing out the importance of fabric bending stiffness during shaping process for fabrication of composites.[85] A 3D orthogonal woven Pi-joint element used in an I beam construction has shown significant advantage in the load bearing capacity of the joint,[86] also resulting in simplified manufacture of the I beam. Modeling studies have predicted localized compression at binder cross-over points.[87] Generic stiffness models have been developed to predict the engineering elastic properties, which compares well with experimental data.[88] Noobed technology has been used to understand the mechanical properties and damage progression in a vascularized 3D woven textile composite subject to in-plane tension.[89] 3D orthogonal structures are good candidate materials for ballistic impact as is evident from several reports such as understanding of the stress wave propagation and damage mechanism,[90] numerical simulation of ballistic impact, damage & penetration,[91] effect of different inclination angles of Z Tows[92] etc. The crimped portions of the Z tows enhance damage tolerance due to unique energy absorption mechanisms and the damage mechanisms unique to the 3D systems include straining and fracture of the z-reinforcement tows.[93] Compared to aluminum of equivalent thickness, 3D orthogonal composites are more impact resistant, making it suitable candidate for aircrafts and high speed vehicles design.[94] Composites made of angle interlock structures (Figure 3) exhibit remarkable interlaminar properties that aid damage suppression and delay in crack propagation.[95]

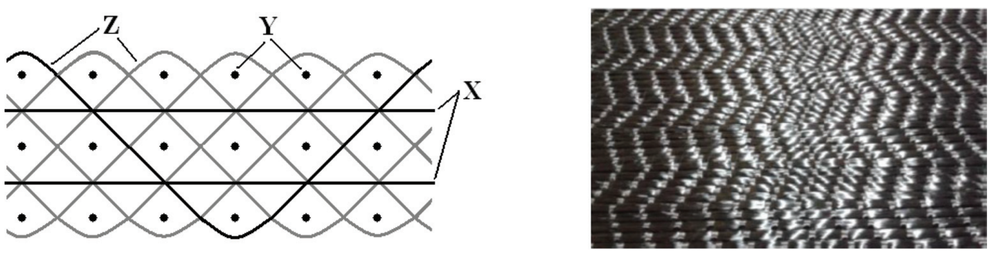


***Figure 3:*** Line diagram of angle interlock weave pattern and the characteristic wave pattern of the woven surface.[40]

Mechanical performance has been shown to be affected by the waviness of the load-carrying fibres, determined by fibre architectures.[96] Significant resistance to delamination and impact damage has been observed in 3D layer-to-layer angle interlock fabrics with formability (adapting to contour requirements) properties. Applications are in rotor blades, landing gears, bullet proof vests and vehicles, front end and leading edges of ships and boat hulls, and show sensitive to slamming.[97] Fibre volume fraction is usually 40–50% due to inherent spaces between yarns with a rare threshold of 60%.[68] Specific advantages of 3D angle interlock woven composites could be a monolithic structure with enhanced delamination resistance, impact/fracture resistance, damage tolerance and dimensional stability, while achieving higher through-the-thickness elastic and strength properties.[98] Stiffness properties have been modeled and compared with experimental data.[99] Compressive behavior at strain rates of 800/s, 1600/s and 2100/s have shown that the stress-strain curves are sensitive to strain rate, and the compressive modulus linearly increases with strain rate while the failure strain decreases with the it.[100] Though thickness permeability of 3D fabrics is found to be higher than that of a typical 2D fabric, flow enhancing through thickness channels in the structure of the 3D reinforcement are formed around the binder yarns.[101] Compared to orthogonal composites, works on angle interlock composites are relatively less in number. However, the commercial viability of developing these types of preforms using modified 2D machinery line has resulted in wide exploration of their prospects by the composite community.

Three dimensional weaving based on dual direction shedding[42] is a very specific and complex 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 to be carried out in both the horizontal and vertical planes. The complete weaving cycle is detailed in Figure 4. Figure 4a shows the grid like warp arrangement. Figures 4b to 4g show half the weaving cycle and Figures 4h to 4m show the other half of the weaving cycle required for the completion of 3D weaving. Figure 4n shows the cross-section of the 3D woven preform. This technology, however, calls for custom designing of machine from the drawing board as the X threads converge, and need to be moved in both the planes to form respective sheds; weft insertion device is positive and requires to be designed for narrow shed widths with simultaneous insertion capabilities. Beat-up device needs to be radically

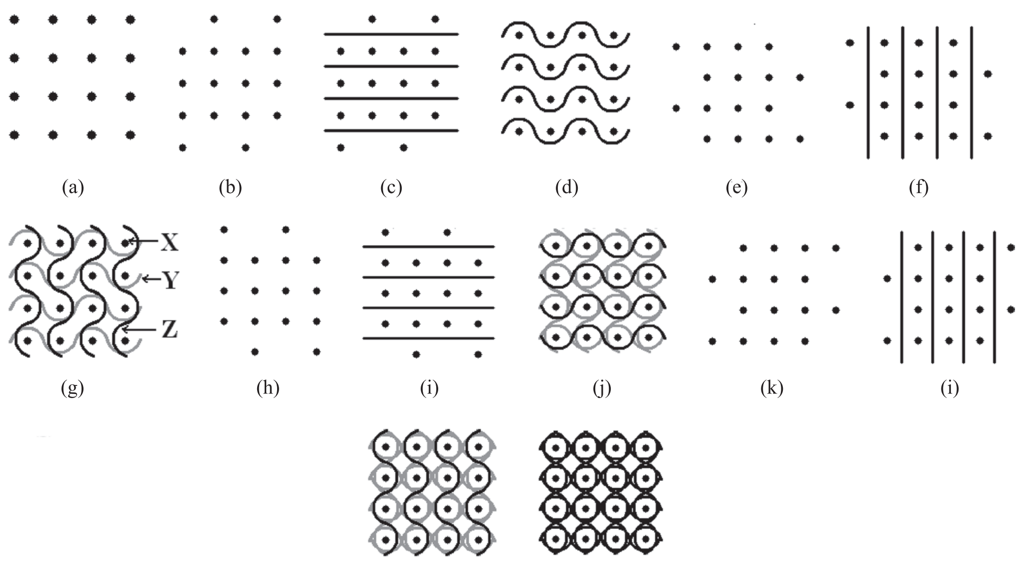


***Figure 4:*** 3D dual direction shedding weaving approach; (a) Grid like warp arrangement (Neutral position); (b)Vertical shedding; (c) Horizontal pick insertion; (d) Neutral position; (e) Horizontal shedding; (f) Vertical weft insertion; (g) Neutral position & completion of half weaving cycle; (h) 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.

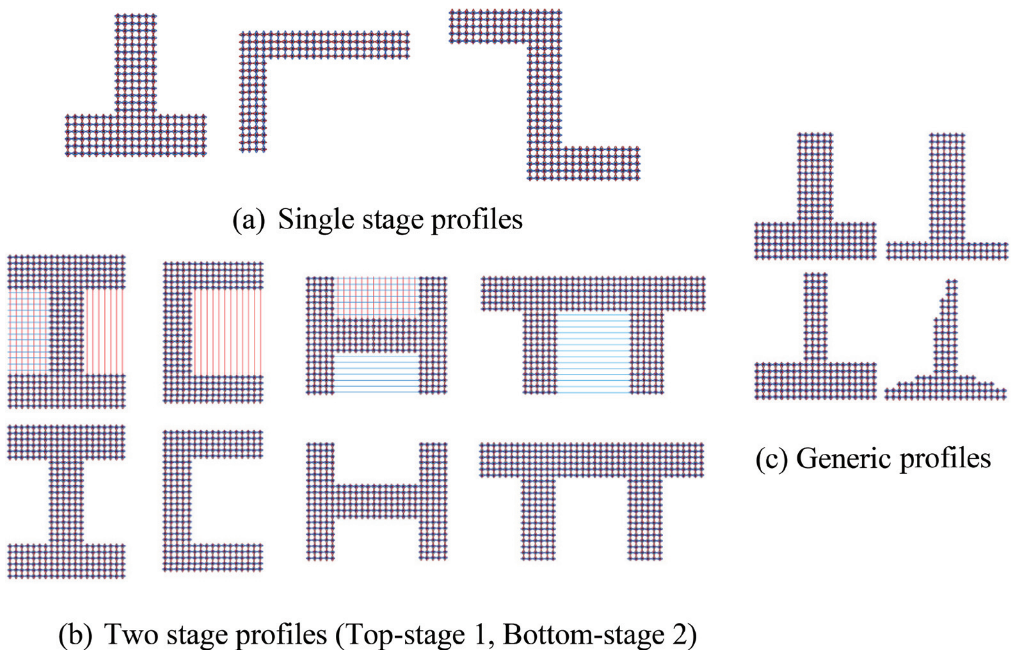


***Figure 5:*** Possible profiles by 3D weaving.

different from the conventional reed system and the take-up system would be linear adaptable to specific profile in question. Specific warp arrangement would be required for specific profiles (Figure 5). Three broad types of profiles viz., single stage profiles (Figure 5a), two-stage profiles (Figure 5b) and generic profiles (Figure 5c) 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 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. However, geometrical limitations exist for cross-sections beyond 200 × 200 mm, the other issue is that only a few researchers are attempting this, due to the complexity and the uncertainties associated with the technology development.

## 4 What is the Future?

Tailored fibre placement[102] combined with tufting and optical fibre sensing for complex composite components is being attempted using a standard off-the-shelf robotic head integrated with a tufting head. Fibres are laid as per desired direction and to the required thickness by the robotic head. Once the required preform stack is built, the tufting head integrates them together using the tufting principle. This process is advantageous over other processes, in that, any desired fibre placement requirement like 0, 90, ±45 can be carried out over the other conventional 3D processes. However, the limitations of the tufting technology and non-interlacement within the architecture exist. Mechatonic approach[103] has been adopted to develop near net shape performs with minimum yarn distortions and flexible motions, thus demonstrating the feasibility of robotic approach to create complex geometries.

3D reinforcement technologies play promising roles in a wide variety of applications,[104] 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. Incorporation of 3D reinforcements requires redesigning of the component,[105] and sometimes even the surrounding structure, and the manner in which they could be coupled. Use of 3D technologies requires a means of bias yarn introduction,[106] since some of the applications require interlacement of non-orthogonal yarns and the requirement to create local features in the component.

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, and attainment of structurally robust thin skins (less than 1 mm). They also have a role to play in hypervelocity impact conditions[107] that are most likely to occur on space craft in low earth orbit (LEO, 200–1000 Km altitude). Here the components currently made of PMCs (antenna struts, panels and low distortion frames) that 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 of thermal gradients (>1500°C per mm), embedment of alloy struts in the weave to enable joining of a hot ceramic skin to other structures such as a structurally efficient truss sub-structure while protecting the skin from thermal stresses.[108,109] Representative Rocket nozzles, thermal protection systems and hypersonic flow path components have been demonstrated successfully using 3D reinforcement technologies.[110,111]

Opportunities exist in terms of improved through thickness properties, automation possibilities using lean manufacturing concepts, revolutionary approaches to meet performance requirements and simplified designs with broad based solutions for structural and thermal applications. They can contribute to a wide arena of applications ranging from space, aerospace, defense, automobile, medical to just name a few. The challenges for 3D composites start with the machinery for 3D reinforcements as till-date there is no commercial 3D weaving machine available. Other challenges include the identification of required weave architecture for the particular end use. Developing bias orientations, achieving desired fibre content in the required directions, compaction issues etc., need to be addressed. At the next level, renewed design of composite tooling, RTM processing, understanding the flow front and related modeling, integration dynamics with 2D/metal counterparts are required to be addressed. Finally, the approaches for out-of-plane testing starting from the fixture development to the test standards need to be evolved.

In a nutshell, while 3D technologies cannot provide any off the shelf solutions, they have the potential to revolutionize, simplify, and make a land-mark contribution to the design and development of composite structures as the textile reinforcement will be specifically-designed into and not made for the part in question.

## 5 Nomenclature & Definitions

Noobing: Non-interlaced development of 3D performs with yarn arrangements in X, Y & Z directions

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

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

Thread density: Yarn spacing per unit length of the fabric

Crimp: Wavy path of the yarn

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