

Advances in 3D Textiles

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List of Contributors

- A. Bogdanovich** North Carolina State University, Raleigh, NC, USA
- F. Boussu** ENSAIT – GEMTEX Laboratory, Roubaix, France
- D. Buecher** RWTH Aachen University, Aachen, Germany
- A. Buesgen** Niederrhein University of Applied Sciences, Moenchengladbach, Germany
- X. Chen** The University of Manchester, Manchester, UK
- C. Dufour** ENSAIT – GEMTEX Laboratory, Roubaix, France
- S. Eriksson** University of Borås, Borås, Sweden
- Y.-S. Gloy** RWTH Aachen University, Aachen, Germany
- R.H. Gong** The University of Manchester, Manchester, UK
- T. Gries** Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany
- J.W.S. Hearle** TexEng Software Ltd, Manchester, UK
- H. Hu** Hong Kong Polytechnic University, Hong Kong, China
- M. Amirul (Amir) Islam** Bally Ribbon Mills, Bally, PA, USA
- T. Islam** RWTH Aachen University, Aachen, Germany
- F. Ko** University of British Columbia, Vancouver, BC, Canada
- I. Kurcak** RWTH Aachen University, Aachen, Germany
- Y. Liu** Hong Kong Polytechnic University, Hong Kong, China
- A. McGonagle** RWTH Aachen University, Aachen, Germany
- P. Pineau** MECACORP, Centre Technique Moteur, Lens, France

A. Prichard Prichard Consulting LLC, USA

L. Sandsjö University of Borås, Borås, Sweden

T. Sontag Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany

D. Soulat ENSAIT – GEMTEX Laboratory, Roubaix, France

D. Sun Heriot-Watt University, Edinburgh, UK

L.W. Taylor The University of Manchester, Manchester, UK

P. Wang ENSAIT – GEMTEX Laboratory, Roubaix, France

H. Yang University of British Columbia, Vancouver, BC, Canada

Nodal three-dimensional woven textiles

5

L.W. Taylor, X. Chen

The University of Manchester, Manchester, UK

5.1 Introduction

Truss configurations provide a reinforcing structure from the inherent geometrical assembly of its strut members. The truss configuration, the framework, strut dimension, number of struts and angle orientations of struts are established through the required integrity of the truss according to the end application (Packer and Henderson, 1997). In a truss structure, strut members of either hollow or solid forms are joined together to either form a node or connect to a separate node via a chosen joining and/or bonding process. Traditional methods of joining include bolts, welding and various adhesives, providing various strengths and also faults to overcome. The current state of the art for truss assemblies evidences a variety of innovative designs in joining struts (Osterberg, 2003; Junjiro and Kiyoshi, 1990). The variability of the number and angle orientations of adjoining struts are due to the adaptability of the node. The node is designed to fit into a strut, or fit over a strut, due to the node being either the full circumference of the strut or part of it (Laforge, 2004). Typically material choices for truss structures tend to be nontextile materials, such as wood and metal, although fibre assemblies are now being utilised once combined with a secondary dissimilar material to ensure a rigid composite fabrication. All truss configurations have the same function: to provide strength and support within a variety of environments that impart loads over the truss configuration, both along the strut length and at the point of strut-to-strut intersection, the node point (Ferrotti and Fabbri, 1992). The relationship between the overall truss form, that is, the triangular truss, and box truss profiles and the full integration and/or joining of the node-to-strut provides an array of design possibilities for supportive truss configurations.

There are numerous node designs, each one vying to eliminate the previous one by becoming lighter, becoming more adaptable and reducing the range of bonding requirements. A variety of materials in fibrous form, including those used in the composites industry, are now becoming evident in this progression toward lighter fully integrated truss structures. Together with the reduction of joins, inherent problems of bonding are resolved by adapting the design into an optimum fully integrated truss frame (Nelson, 2003). The truss configuration can be in the 2D plane, known as a planar truss structure, or when combining 2D truss configurations in one complete structure, producing a 3D form.

Truss terminology is established by the combination of geometric shapes to generate the required truss framework. Due to the many geometric configurations,

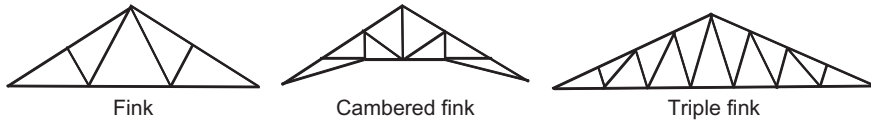


Figure 5.1 2D planar fink derivative truss configurations.

the nomenclature of the planar truss is varied. With each initial basic configuration there is a derivative, which may also include an aspect of another truss's framework, such as the fink truss configurations in Figure 5.1.

Innovative technological advances, both in terms of manufacturing capabilities and raw materials, allow for new concepts (Ambrose, 1994) that advance the truss configuration geometry, 2D-to-3D formation and material choices; alternative end applications and markets can then utilise this versatile structure. The range of nodal 3D woven structure (N3DWS) configurations stems from the breadth of current truss configurations, both 2D and 3D frameworks. The research and development of 3D shape weaving, using conventional weaving technology and associated weave architectures, allows the formation of the N3DWS for technical applications.

Combining the weaving principles with the tailoring of the X weft, Y warp and Z through thickness yarn interlockings, the weave design process allows a variety of multilevel, multilayer compound structures. Variations on integrating the warp/weft levels-layers allows hollow, solid or a combination of woven panels and shapes to be produced within the weaving cycle. The tailoring capabilities of the varying yarns, together with the employment of high-performance yarns, allows the woven textile product, the N3DWS, to meet a range of engineering tolerances and ultimately perform in technical applications.

The N3DWS is composed of hollow tubular forms (pockets) within a 2D woven fabric plane. The integrity of the nodal's configuration is achieved through the compounding of a surrounding outer solid woven panel. This outer solid woven panel can either be removed or remain as part of the woven truss, dependent on the requirements of the end application. The integral outer woven panel has its own weave architecture to that of the N3DWS. Both the nodal and outer wall weave architectures are established via performance requirements and required formation off loom from 2D-to-3D. The integral wall does allow the N3DWS to be adapted to alternative end uses, which will be put forward within the future trends section. The N3DWS is woven flatly, when the completed woven configuration is removed from the loom, and from the associated tension constraints, the nodal structure is pulled into shape. The maintenance of the circumference of each strut and at the concluding node point, from the strut-to-strut intersection, is achievable through the combination of varying multilevel, multilayer weaves.

There are many variables to consider within the design and production stages of the N3DWS that will be discussed throughout this chapter. Performance capabilities of the N3DWS are dependent on both the raw materials used within a yarn form and the combination of varying multilevel, multilayer weave architectures. Within the

design stages and application of weave architectures, the yarn interlockings within the production of the N3DWS need to consider the following:

- integral fabrication;
- hollow divisions within solid wall fabrications;
- strut member dimensions, number of struts and angle orientations of struts to one another;
- node point; and
- nodal configuration.

The initial development stages of the N3DWS require the translation of the 3D truss geometries into a 2D planar truss schematic. To account for all the warp/weft levels-layers associated to the solid outer wall and hollow nodal formation, the 2D truss schematic is placed onto a graph format within a commercially available woven textile CAD/CAM programme. This allows the application and visualisation of segmentations and defined boundary zones, which will be assigned their relevant weave architecture. The N3DWS's finalised 2D schematic, together with the completed combination of weave architectures, are then finalised within a CAD programme before the weaving production stages. To remove an element of the labour intensive process the automation of the N3DWS was established via a library of strut-to-strut assemblies and weave architectures within an in-house CAD programme (Smith and Chen, 2009a,b) for the production of a generic nodal configuration. The manual and automation aspects of the N3DWS, and the design preparation and production process together with an overview of the weaving technology, both employed and with future technology visions shall be put forward in this chapter.

Variations of weave architectures, deriving predominantly from multilevel, multilayer compound structures will remove the potential of the N3DWS from some markets. The N3DWS is a product defined by its end market; its market application is established via the raw materials in yarn form, and the configuration is limited by the weaving technology employed.

5.2 Nodal 3D structures

On the whole the majority of truss designs are not produced as a complete fully fashioned integrated structure. The varying truss frameworks of joining struts to a node are designed according to the requirements of the end application. This equates to an infinity of strut-to-strut intersecting possibilities and manufacturing routes. The characteristics of a truss structure are the joining of a solid or hollow strut member to a node. The integrated struts within a truss configuration can have similar or varying cross-sections. The node is a point of connection that can be constructed integrally to the strut or as a separate component. To acknowledge the N3DWS's place within the fibrous truss domain, and in relation to the strut's integral node, the classification of shape configuration, fabrication process and structure produced within or outside the 2D fabric plane is now established (Chen et al., 2011; Taylor and Chen, 2015), which can be seen in Table 5.1.

Table 5.1 Nodal plane dimension and production classification

Structure	Fabrication process	Architecture	Shape
Nodal 3D 2D planar	0/90° Weaving Technology	Multilayer multilevel Angle interlock derivatives	The joining of woven hollow tubular structures constructed within a solid woven architecture within the inner 2D fabric plane
Nodal 3D 3D planar	In-plane and outer plane weaving process	Multilayer multilevel Angle interlock derivatives	The joining of woven hollow tubular structures constructed within a solid woven architecture within both the inner and outer 2D fabric planes
Nodal 3D truss	Alternative fibre/yarn assemblies	N/A	The production and fabrication of strut members and nodes

5.2.1 Fabric formation: 2D planar truss structure

The 2D planar truss structures are comprised of a series of individual fibrous fabricated layers that are connected to each other by additional fibrous layer(s). The first structure of this category can be found within the work of [Brogan and Walsh \(1980\)](#). Two woven fabric layers, a top and bottom layer, are connected by the placement of individual fibrous hollow struts that have a triangular cross section in between the outer layers. The whole structure can be manufactured from a range of materials and fabrication processes. This approach requires an additional bonding procedure, typically via resin impregnation. Additional triangular strut members, layers can be inserted between the outer top and bottom layer generating a deeper 2D planar truss panel.

A similar truss structure was created previously by [Rheaume \(1976\)](#), utilising weaving technology to manufacture an integrated multilayer 2D planar truss structure. It is comprised of a top and bottom woven fabric that is connected by a middle woven layer at predetermined points. The middle woven layer creates a triangular cross-sectional configuration within, by the interlacement to the outer fabric layer after extending between the two. The middle layer interlocks into the top layer after weaving independently for a determined length and then connects via the interlocking with the bottom layer, also after weaving independently for a given length. This woven construction is also known as a trapezoid fabric.

Remaining with the production of woven multilayer fabrics constructed to form a truss configuration in the fabric plane, due to the nature of the conventional weaving process, the works of [Lowe \(1987\)](#) and [Day et al. \(1990\)](#) have paved the way for the classification of the 2D planar truss configuration. In the fabric plane, woven truss configurations developed from the requirement for secure bifurcated and trifurcated

textile grafts, encourages research into seams, yarn locations, off-loom manipulation and finishing processes. This allows the manipulation of the inherent properties of the yarns employed. A design by [Matterson \(1985\)](#) allowed the designing of curved, straight and bifurcated tubes with integrally woven seams. To prevent wastage, the shapes are woven side-by-side along the warp direction. Using the techniques of double cloth it changes the directions of the top and bottom levels to allow an interchanging joining point, which interlocks the two woven levels. The constructed woven tube is maintained by two narrow woven tubes on either side of the bifurcated shape, acting as seams. The tubes are woven with the weft being its longitudinal direction, requiring the weft to interlock the warp in a tapered manner to gradually form the V part of the Y, forming a perfect closing point at the crotch area.

5.2.2 Fabric formation: 2D planar and 3D truss combinations

Utilising a triangular cross section to form a truss inspired configuration, [Logan \(1983\)](#) employed fibreglass tape yarns to form an outer top and bottom layer. The outer layers are connected by another tape yarn in-between the two outer layers, thereby producing the truss structure. The objective of this manufacturing route was to reduce labour time and costs by producing the structure in one cycle. The top and bottom strips are held under tension within a predetermined-sized container, which is spaced apart at the desired height to allow the inner filament strip to connect to the top and bottom strips. Resin is injected into the container to provide a rigid supporting structure.

5.2.3 Fabric formation: Alternative truss configurations and assemblies

Fully integral struts and nodes within truss formations have seen innovative production solutions. These derive from a range of manufacturing processes and knowledge of fibrous truss assemblies in composite materials for engineering applications, particularly civil, aerospace and military. Principles of sandwich panel constructions and truss configurations are integral to the work of [Kooistra and Wadley \(2005, 2007\)](#), who also classify these structures as tetrahedral, 3D kagome and pyramidal structures. The struts are integral with the node points as the whole truss structure, initially using metal alloys and metallic bonding in the fabricating process, are produced by punch die tooling, whereby the solid metal sheets are initially perforated and then folded. The completed structure resembles a lattice panel, which is then formed into a 3D structure. The 3D lattice/trusses are then covered by an outer top and bottom flat panel from the same or a differing material. This provides a manufacturing route that can be easily adapted to alter the angle of the struts from the node point. The structure is categorised as a fully integrated truss assembly, although there are some delamination issues due to the bonding application of a top and bottom cover encasing the final truss framework. Alternative outer layer fibrous materials have been employed combined with integral strut and node points of the tetrahedral/3D kagome/pyramidal structures

by Finnegan (2007). Using woven materials, such as bi-axial laminates, evidences an improvement at the intersecting area of the strut and node to the outer layers of the truss-like configuration. This provides a rationale to researching alternative manufacturing processes in the production of integral fibrous fabricated nodal truss structures.

Jensen (2004) and Jensen and Francom (2005) developed and manufactured the IsoTruss. The continuous truss configuration is produced by winding filaments around a mandrel eliminating bonding at the node point. Each node is established when a filament crosses another filament as it is placed in the desired location and direction down the mandrel. It is the inclusion of a node at the point where the filaments overlap and turn to travel in another direction, aided by the helical formation, that allows a variety of cross-sectional configurations to take place.

5.2.4 Fabric formation: N3DWS, 3D-to-2D-to-3D

The production and design of the N3DWS provides a process for fully integral nodes to strut members. Strut-to-node integrity is achieved via the forming of a node area, produced as the hollow woven tubular strut meets another within the desired truss configuration. The weave architectures employed are chosen to maintain the circumference along the length of all strut members and within the node area when the N3DWS is removed from the loom and pulled into shape. The N3DWS provides, based on materials employed, both a flexible and/or a rigid framework of strut members to a node. The node, by definition, provides a network of points from which strut members join to or from. Whether these configurations lie within the 2D plane or extended into a 3D outer fabric plane, the assembly of such planar truss networks depends on the end application and capabilities of the weaving technology. Developing a 2D planar woven truss configuration was the starting point for the generation of the N3DWS.

5.3 Nodal 3D design and production parameters

The range of information, before the flattening stages commences, includes all known dimensions, such as the number of struts, angle orientation of struts, strut diameter and length, wall thickness, density of fabric and the proximity of the individual woven hollow struts to one another. A coordinate system is employed to formulate the weave generation within a graph template, ensuring all yarns are accounted for within the length, width and depth of the intended N3DWS. The weaving cycle entails all yarns to be interlocked, producing a hollow nodal configuration that is entrapped by an outer woven solid panel. The outer woven solid panel literally draws the outline of the nodal configuration within the weaving cycle and keeps the structure together by creating a surrounding seam.

The flattened 2D nodal configuration is established from an approximation of the 3D nodal structure's geometry, which can be seen in Figure 5.2. The relationship of the 3D struts to each other is altered when flattened in a theoretical state, due to the

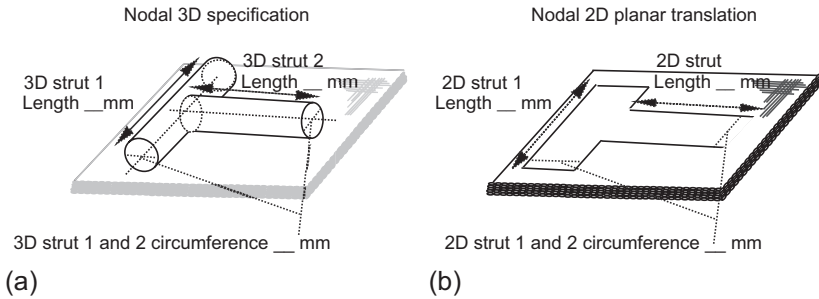


Figure 5.2 3D nodal to 2D nodal format. (a) Nodal 3D specification and (b) nodal 2D planar translation.

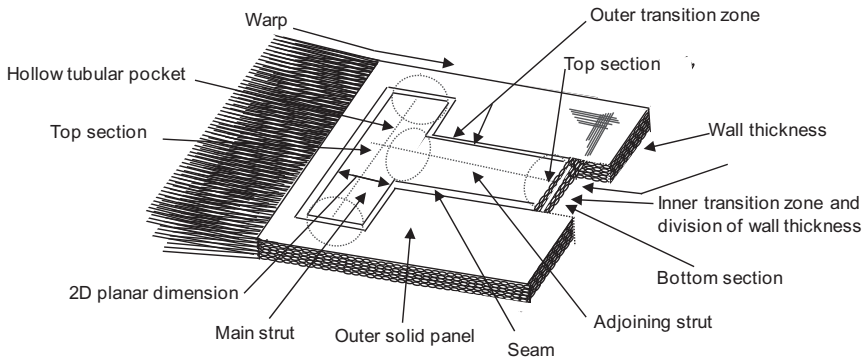


Figure 5.3 Area classification of the 2D nodal configuration within the plane of the fabric.

impossibility of flattening a curved surface without deformation. Within the flattening stages, the struts take on an oblong form adhering closely to the 3D structure within the resulting flattened 2D dimensional configuration. This is known as the 3D-to-2D approximation.

Segmentations are applied when the outline of the flattened 2D nodal structure’s configuration and placement within the fabric plane and wall thickness are known, as identified within Figure 5.3. The finalised nodal and inner and outer segmentations are then transferred into a graph format, either on paper or within a CAD programme, allowing the process to be treated as a 2D graphical nodal configuration. This transition provides key areas for the insertion and containment of varying weave architectures. The combination of segments and insertion of inner weave architectures generates a fully integrated component and large-scale weave plan for production.

The node point geometry and inner and outer segmentation are dictated by the number, dimension and orientation of the struts. It is the node point that establishes the transition zones within the defining boundaries of the segmented areas, seen in Figure 5.4, with regard to the combination of one weave architecture to another. Therefore, the positioning of boundary lines to enclose each segment provides a range