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WEAVING MULTI-LAYER FABRICS FOR REINFORCEMENT OF ENGINEERING COMPONENTS

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B J HILL, R McILHAGGER, P McLAUGHLIN

UNIVERSITY OF ULSTER
Engineering Composites Research Centre

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SUMMARY

This paper assesses the performance of interlinked, multi-layer fabrics and near net shape preforms for engineering applications, woven on a 48 shaft dobby loom using glass, aramid and carbon continuous filament yarns. The interlinking was formed using the warp yarns.

Two basic types of structure have been used. The first used a single warp beam and hence each of the warp yarns followed a similar path to form four layer interlinked reinforcements and preforms. In the second two warp beams were used, one for the interlinking yarns which pass from the top to the bottom layer through-the-thickness of the fabric and vice versa, and the other to provide "straight" yarns in the body of the structure to carry the axial loading. Fabrics up to 15mm in thickness have been constructed with varying amounts of through-the-thickness reinforcement. Tapered T and I sections have also been woven, with the shaping produced by progressive removal of ends during construction.

These fabrics and preforms have been impregnated with resin and cured to form composite samples for testing.

Using these two basic types of construction, the influence of reinforcement construction and the proportion and type of interlinking yarn on the performance of the composite has been assessed.

Preliminary conclusions drawn from this work include:

- it is possible to weave such preforms on standard dobby looms
- there is an optimum proportion of interlinking yarn
- after resin impregnation improved engineering properties have been achieved
- the process has significant economic advantages over conventional prepreg lay-up procedures
- significant reductions in waste can be achieved
- hybrid structures can be produced incorporating a range of generic yarn types

INTRODUCTION

Composite technology has grown considerably since man ascertained that bricks were stronger when straw was included in the clay mixture. Now composite materials are extensively used in the aerospace, automotive, construction and medical industries. Their high strength to weight ratios, ease of processing and the capability of in-building strength in the principal stress directions have given composites an advantage over their metallic counterparts.

Traditional composites are manufactured by superimposing layers of resin impregnated material into a mould prior to curing. The lay-up procedure is carefully controlled to provide the required properties and eliminate spring-back in the finished product. These layered structures are prone to delamination, particularly in bending, leading to catastrophic failure.(1) Research has shown that delamination can be restricted by linking the layers together to give improved through-the-thickness properties.(2,3) Researchers have demonstrated that improved mechanical properties can be achieved by sewing the layers together and that these improvements may be due to the through-the-thickness yarns acting as "crack stoppers".(4,5,6,7) Other researchers have established that three-dimensional flat fabrics offering similar properties can be woven on a conventional loom.(8,9,10,11,12)

It has been demonstrated that composites manufactured from 3-D woven fabrics give improved damage tolerance (13,14, 15) and in addition Hirokawa et al have established that 3-D orthogonal woven composites had better compressive strength and flexural fatigue strength than 2-D composites (16). A further development by McGoldrick et al (17) has shown that velvet structures can be utilised to produce, what they term, 2.5D fabrics to overcome the problem of delamination in composites and Mohamed et al (18) have developed a computerised machine for weaving 3-D orthogonal net shapes. These developments indicate the amount of research being undertaken to develop interlinked woven structures for composites.

At the University of Ulster a 48 shaft computerised dobby loom has been used to weave multi-layered, interlinked fabrics and near net shape components for engineering applications using glass, carbon and aramid yarns.

REINFORCEMENT PRODUCTION

Yarn Selection and Properties

Four types of yarn have been used for this research:

glass (texturised)
glass (continuous filament)
carbon (continuous filament)
aramid (continuous filament)

The tensile strength of these yarns was measured as a straight tensile test and as a loop strength using a Textechno Statimat M instrument. Typical results for the four types of yarn are given in Table 1.

The tensile strength of the continuous filament glass yarn was approximately twice that of the texturised glass yarn and in terms of tenacity about 2.5 times stronger. The tenacity of the continuous filament glass yarn was in turn about half that of the carbon yarn which was about half that of the aramid yarn.

Since the interlinking yarns in the proposed 3-D reinforcements used in this work not only act as "crack stoppers" but are also the strength component holding the layers together, it was considered that a loop test may be a more relevant method of testing the yarn strength than the straight tensile test.

For the texturised glass yarn the loop strength and the straight tensile strength are approximately equal. However, the loop strengths of the other three yarns differ considerably from the straight tensile strength indicating the very poor transverse strength of these highly structured fibres. The loop strengths of the continuous filament glass yarn and the carbon yarn were approximately half that of the respective tensile strengths, whereas the loop strength of the aramid yarn was 67% higher than the tensile strength. This array of tensile and loop strength behaviour gave a range of properties from which it may be possible to draw conclusions about the influence of yarn properties on reinforcement and composite behaviour and performance.

Three-Dimensional Weaving

A series of reinforcements was woven in plain weave constructions using the 1460 tex texturised glass yarn. These were 4-layer interlinked structures with all the warp yarns being used to form the through-the-thickness (Z) element. The structures all weighed about 3500 g/sqm and were approximately 4.5 mm in thickness. They were woven with Z-direction reinforcement in the range 6.9% and 18.5%. Difficulties were encountered in testing the tensile strength of some of these reinforcements because of breakage at the clamps.(19,20)

The data gained from these trials was used for the production of two sets of T-section preforms, one from the texturised glass yarn and one from a straight continuous filament yarn. The T-sections were woven with a four-layer stem or web and with a two-layer flange. As in the case of the interlinked fabrics the basic structure for each layer was a plain weave with each warp end within the reinforcement structure being involved equally in the interlinking or "stitching" together of the layers. The interlinking in the 4 layer segment was formed by transferring warp ends from layer 1 to layer 3 and from layer 2 to layer 4 for one pick before returning them to their original position. Similarly ends in layers 3 and 4 were transferred to layers 1 and 2 respectively and back. This is illustrated in Fig 1 with one end interlinking from layer 1 to layer 3. The formation of a warp link over one pick has been found to give the optimum results as far as performance properties of structural components are concerned. All the warp ends did not form the interlink at the same pick but were staggered so as to avoid possible lines of weakness. The type of construction used creates symmetry about the mid-plane. In this way it was hoped to reduce any tendency for the composite component to spring back after impregnation with resin and curing.

T-section preforms were woven with the Z proportion ranging from 3.2% to 18.5% (Fig 2). In order to assess the effectiveness and the optimum amount of the through-the-thickness element, a strength test was devised for these T-section preforms whereby the ends of the flanges were clamped in a tensile testing machine and the force to pull the web apart through its centre plane was measured. This force was termed the interplane strength, and was measured by clamping the full width (50mm) of the samples in the jaws of the tensile machine and as a grab test where the centre 25mm was held. Results indicated that there was an approximate linear relationship between percentage Z element and interplane strength up to 10% to 12% after which the increase tailed off. The most important feature of these tests was a visualisation of the mode of breakdown. This implied that the effects of the through-the-thickness element on the interplane strength are complex and that the construction of the T-section at the juncture where the construction changes from a pair of double interlinked layers to four interlinked layers is critical.

After impregnation and curing of these T-sections, a similar strength test was undertaken. Results from this indicated that the Z element does not have a significant effect on the initial failure of the composite component but considerably improved the energy absorbing properties of the composite in interplane strength.(Fig 3) The visualisation of the mode of breakdown indicated that the resin impregnated component broke down in a significantly different manner to the fabric reinforcement, with the latter being able to deform in the area between the clamps whereas the resin prevents the component from taking up this configuration. This behavioural difference in testing between the reinforcement and composite has forced us to question the validity of using fabric strength results to measure the effectiveness of the through-the-thickness yarn.

The interlinking and construction of these fabrics and preforms has been accomplished by using plain weave structures. This introduced crimp into the yarns in the structure, especially in the warp direction which may also be the direction of the principal stress. From an engineering standpoint the yarns should be preferably in as straight a line as possible, ideally with no crimp. In order to optimise the fibre properties a further series of reinforcements was woven using T300 carbon (12k) yarn. In this series the fabrics were woven with layers of straight warp yarns interspaced with straight weft yarns with no interweaving, the structure was held together by using two further layers of warp yarns one on the top of the reinforcement and the other on the bottom. These interlinking warp layers bound the reinforcement together by being woven from the top face to the bottom face and vice versa. As in the previous structures this interlinking was over one pick before returning to the original face.(Fig 4)

Different face weave patterns and different interlinking yarn counts were chosen to give a range of through-the-thickness proportions from 2% to 18%. The reinforcements were woven on a shuttle loom and so further binding was achieved by the selvedge. This is an important factor in the transfer of the preform from the loom to the resin impregnation process. Depending on the number of layers structures from 3.5mm to 15mm were woven. These have not yet been impregnated but it is envisaged, based on previous research, that the composites will be 2.7 to 12mm thick with a 55 to 60 per cent fibre volume fraction. The analysis of the woven structures is given in Table 2.

One of the problems encountered during weaving was filamentation of the filaments against the outside edges of the headles holding the warp yarns lying in the same vertical plane.(Fig 5) This problem can be overcome by modifying the headles, but this may limit the types of construction which can be produced. The seriousness of this limitation has not been fully investigated yet.

Aramid yarns were used to construct a similar series of reinforcements to those woven from the T300 carbon yarns. For these fabrics five layers of straight warp were interspaced with seven layers of weft, none of these layers was interwoven. A coherent structure was formed by linking two further layers of warp yarns from the top and bottom faces, in a analogous manner to the carbon samples. The fabrics ranged in thickness from 4.0mm to 10.4mm and with a weight range of approximately 4000g/sqm to 7500g/sqm. The problem of filamentation found with the carbon yarns did not occur with the aramid yarns. Details are given in Table 3.

Preform Production

One of the issues of conventional composites made by the lay-up route is the production of trimming waste; this would be a major problem in the mass production industries eg automotive industry. In an attempt to overcome this it was concluded that tests should be made to create near-net shape components on the loom. The T-section preforms, previously discussed, were the first attempt, since this configuration is a much used load bearing component in the engineering industry. As was stated earlier, these interlinked T-section composites while exhibiting better energy absorbing properties than their laid-up counterparts were still not ideal in their construction. In the area where the structure changed from 4-layers to 2 layers a cleavage zone was created where the structure was opened out to form the T-section shape, giving a resin rich seam. The cleavage was formed because the yarn paths in all four layers of the interlinked structure were identical.(Fig 6) Trials are being conducted to try to overcome this problem by using different weave structures in each of the layers or modifying the structure at the juncture of the interlinking layers, so that when the preform is folded to form the T-piece, a gap is not formed at the line of separation between the 4-layer and 2-layer structures.

However, this research has shown that near net shape preforms can be woven on a conventional loom and that there is the potential for significantly reducing waste.

While there are significant advantages in producing uniform cross-section near net shape components on the loom there would be an even greater advantage if tapered and other sections could be produced. The initial research at the University of Ulster has examined the feasibility of weaving these shaped preforms using cotton yarns of different colours in each of the layers so that the yarn paths could be followed.(21) Shaped I-sections were woven with the shaping produced by dropping out selected warp yarns until the required shape was produced. The samples were woven with 4 and 6 interlinked layers as the centre web of the section with this dividing into 2 and 3 interlinked layers to form the flange.(Fig 7)

Further trials have been conducted on the weaving of 4 layer open ended box shapes with tapered ends. These multi-layer shapes are seamless and can be designed to be a precision fit product that can be placed over a mould. (Fig 8)

Components have been woven with localised reinforcement in either the warp or weft direction. These areas of localised reinforcement can be rectangular or tapered. The base fabric was woven with three interlinked layers with the localised reinforcement either six or ten layers in thickness. (Fig 9, Fig 10)

These trials have indicated that the loom is a very versatile machine for preform production and that it is possible to manufacture a great many of the shapes required by the engineering and medical industries. However, a number of problems still exist, for example yarn path length which could be overcome by examining weave structures. The shaping of preforms was performed by leaving out selected yarns; this produced waste which could make the process uneconomic. Reductions in the amount of waste could be achieved by utilising these "free" yarns in other structures in a manner similar to nesting in engineering or lay planning in the clothing industry. Nevertheless, if shaping is to be achieved then some waste is inevitable. Research on these problems continues.

The weaving process lends itself easily to the production of hybrid structures where yarns of a different composition to the base reinforcement are introduced. These yarns can be inserted in either the warp or weft direction and in any position in the three dimensional structure. This versatility makes the loom a very powerful tool in the manufacture of composite reinforcements. It should be noted that weaving is not the only method used to manufacture composite reinforcements and that for certain end uses one or more of the other methods may be more suited.

Economics

A theoretical assessment of the economic feasibility of weaving three-dimension interlinked fabrics was undertaken. A comparison was made of the cost of producing a component by the convention lay-up technique against the cost of manufacture using a woven three-dimensional fabric.

A number of assumptions were made:

- Yarn costs were the same for both processes,
- Weaving costs were based on the rate of pick insertion,
- The same total weight of both types of fabric,
- Cutting waste was the same for both processes,
- Actual labour costs in hand lay-up were used,

- After lay-up the cost of both processes was the same,
- No major capital was required for the 3-D weaving,
- No account of overheads or depreciation were taken into account.

Taking account of a longer time to set up the loom to weave the three dimensional fabric, and this only has marginal influence on the final cost, it was concluded that at weaving speeds of 40 to 50 picks per minute the cost of the component made from the 3-D fabric would be cheaper than the conventional lay-up component.

However, a number of disadvantages must be considered:
In the lay-up method plies can be oriented in any direction; this is not the case with 3D fabrics where only the two mutually perpendicular directions can be achieved. Using the lay-up method, components of any thickness and profile can be manufactured. 3-D weaving is restricted, at present, to a relatively small number of plies, thereafter, the product is laid up in the conventional manner. Profiling is not yet readily achieved on a conventional loom without significant waste implications.

Nevertheless, this limited economic assessment of the process together with a visualisation of its potential and an understanding of the needs of industry has led the researchers at the University of Ulster to conclude that the operation has considerable potential.

CONCLUSIONS

This paper has shown that it is possible to weave three dimensional multi-layer interlinked fabrics on a dobby loom. Shaped preforms can also be woven with uniform and tapered cross-sections provided care is taken with the choice of structure. It is probable that improvements to these structures are possible with slight modification to the loom, especially the headles.

Three-dimensional fabrics give improved engineering properties over conventional composites made by the lay-up method.

The economics of the process, in theory, give possible benefits over the traditional method, with considerable potential for reduction in the production of waste.

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TABLES

Table 1 Yarn Strength Properties

	Yarn Count tex	Strength N	Extension at Break %	Tenacity cN/tex
		Tensile Strength		
Texturised Glass	1460	191	2.50	13.1
Continuous Filament Glass	1200	381	2.90	31.8
Carbon	814	501	1.72	61.6
Aramid	836	1096	4.03	131.2
		Loop strength		
Texturised Glass	1460	195.6	2.45	13.4
Continuous Filament Glass	1200	199.2	1.71	16.6
Carbon	814	289.0	0.89	35.5
Kevlar 49	836	1839.2	4.17	220.0

Table 2 Analysis of Carbon Typical Structures

Straight Warp Layers	Straight Weft Layers	Interlinking Yarn	Thickness mm	Weight g/sqm
3x12k	4x12k	2x3k	3.5	2896
5x12k(2)	6x12k(2)	2x12k(2)	5.4	4227
5x12k(2)	6x12k(2)	2x12k(2)	8.3	5125
19x12k(2)	21x12k(2)	2x12k(2)	15.0	12690

Table 3 Analysis of Aramid Typical Structures

Straight Warp Layers	Straight Weft Layers	Interlinking Yarn	Thickness mm	Weight g/sqm
5x7900d'tex	7x7900d'tex	2x7900d'tex	4.0	3750
5x7900d'tex	7x7900d'tex	2x7900d'tex	7.3	7420
5x7900d'tex	7x7900d'tex	2x7900d'tex	10.4	7720

FIGURES

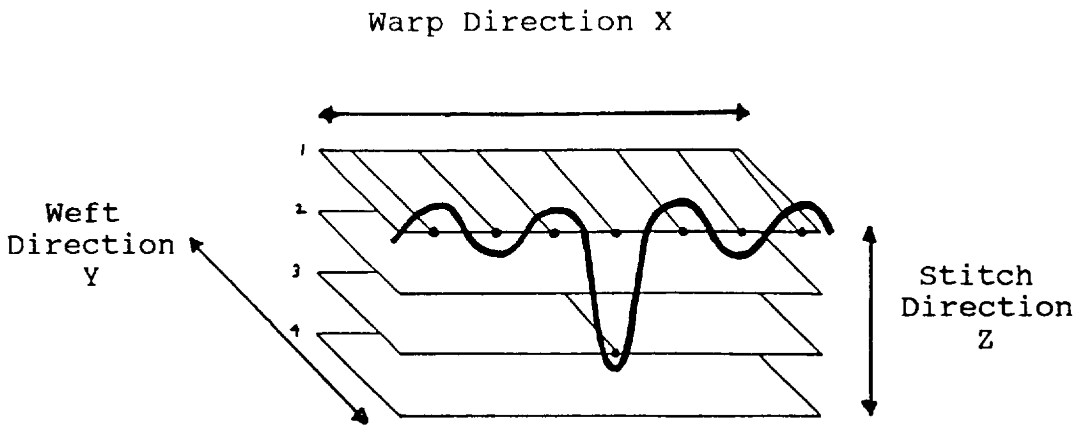

Fig 1 Warp Stitching

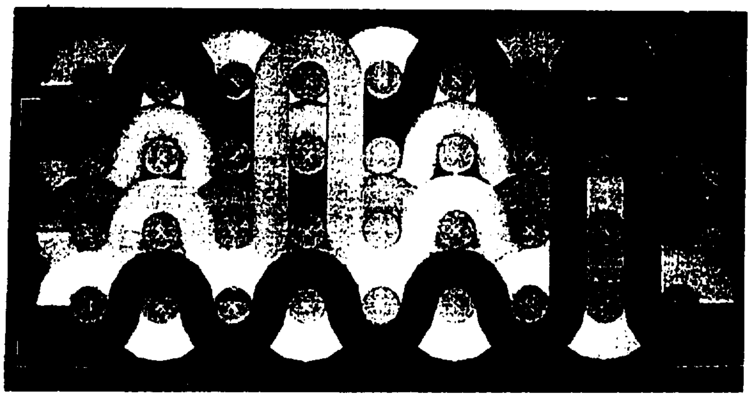

Fig 2 Weave Structure of Plain Weave T-Section

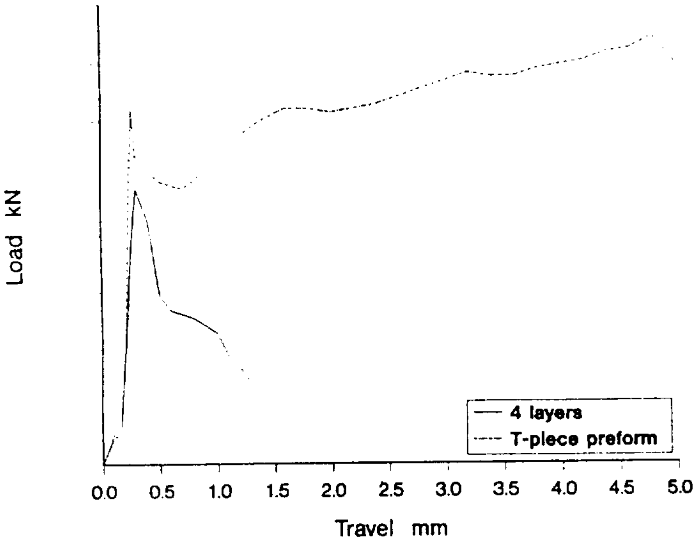

Fig 3 Graph of Load Against Travel

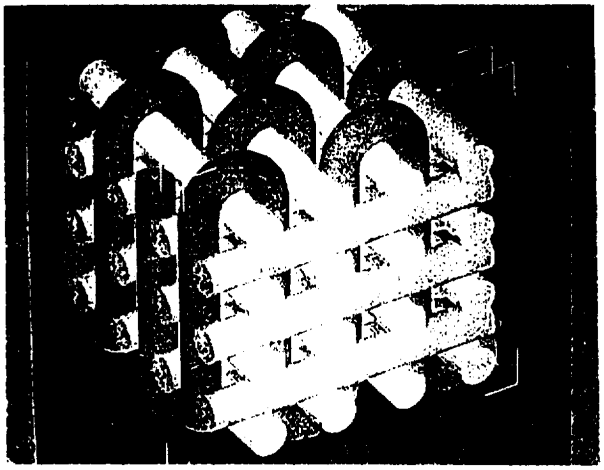

Fig 4 Weave Structure of Interlinked Fabric

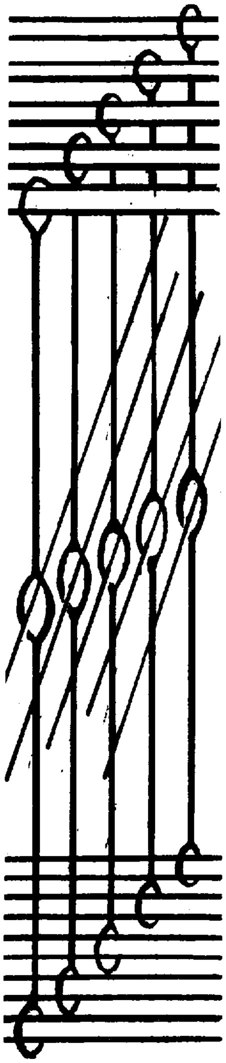

Fig 5 Yarn and Headle Position in Conventional Shafts

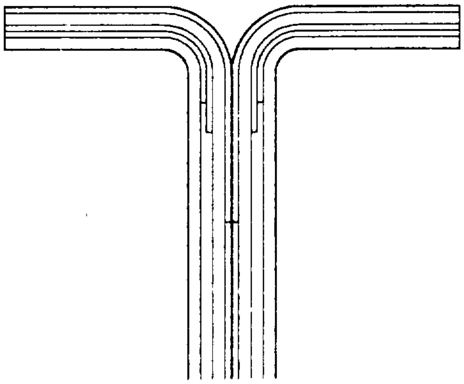

Fig 6 T-Section Illustrating "Cleavage"

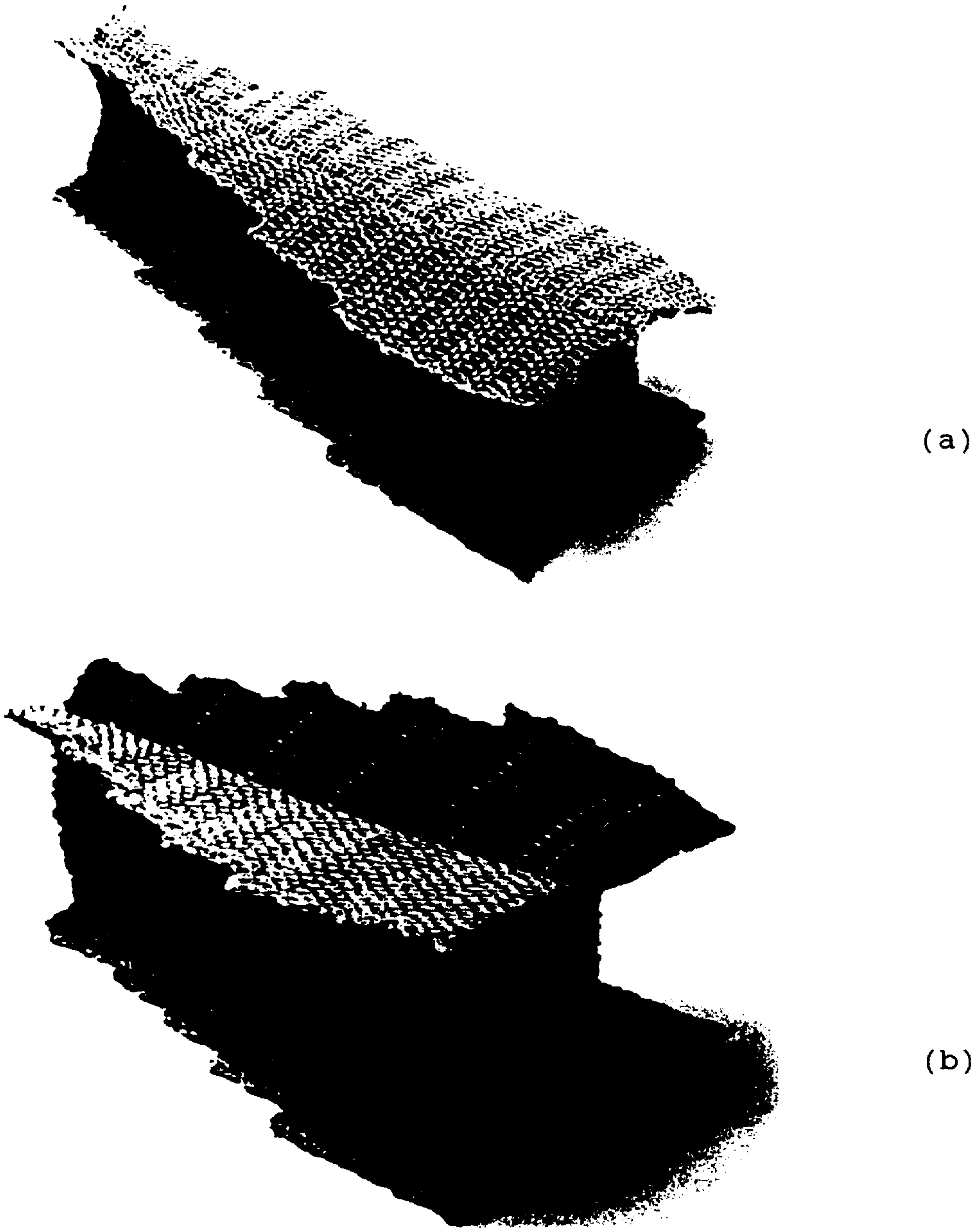

Fig 7 Shaped I-Beam (a) 4 Layer Stem with 2 Layer Flange
(b) 6 Layer Stem with 3 Layer Flange

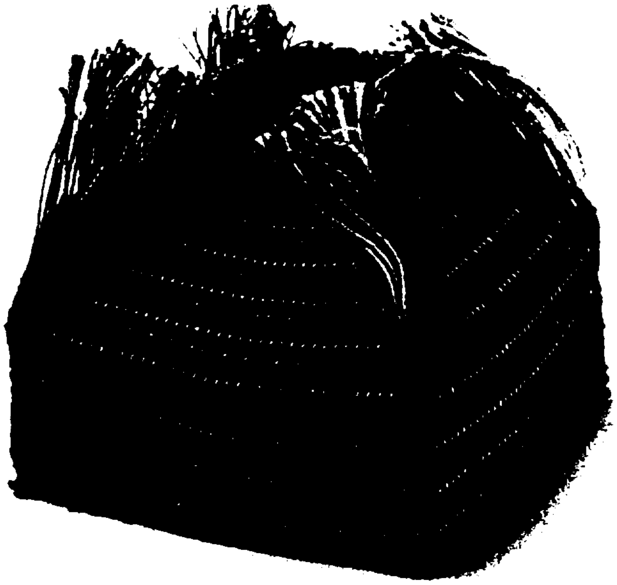

Fig 8 Two Layer Open Ended Shaped Box

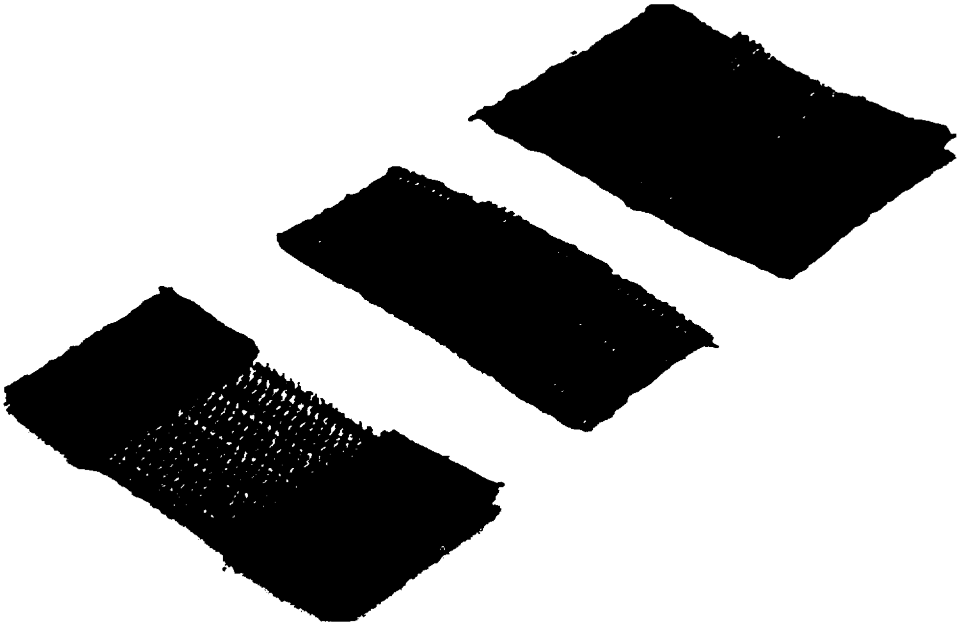

Fig 9 Localised Reinforcement (Warpwise)

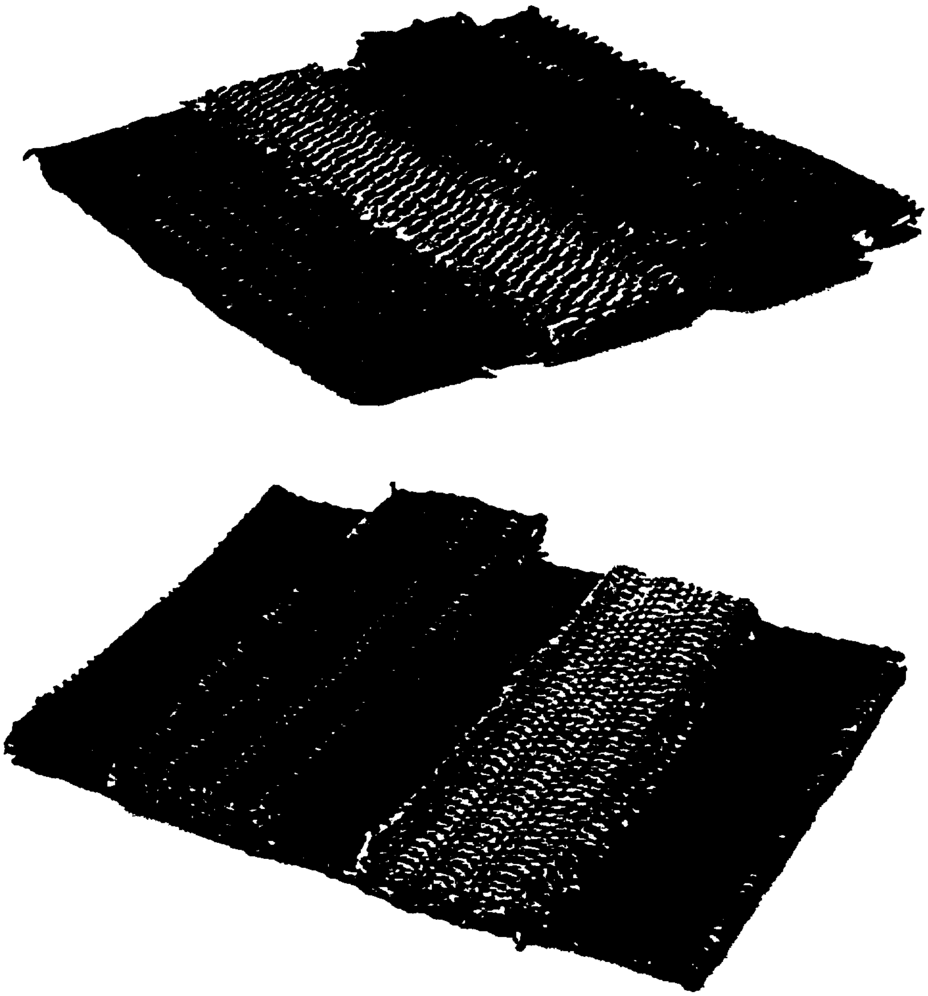

Fig 10 Localised Reinforcement (Weftwise)