dian Journal of Fibre & Textile Research
ol. 25, June 2000, pp. 115-120

Mechanical properties of glass composites based on knitted preforms with inlays

R M V G K Rao
National Aerospace Laboratories, Bangalore 560 017, India
and
G Anand Nahar[a] & R Alagirusamy[b]
P S G College of Technology, Coimbatore 641 004, India

Received 1 April 1999; accepted 6 October 1999

An attempt has been made to improve the mechanical properties of the composites with knitted preforms by introducing horizontal strands in the course direction in a flat-bed knitting machine. Flat knitted preforms were produced with different proportions of axial inlay strands and the composite laminates were prepared using the vacuum-assisted resin transfer moulding technique. It is observed that the introduction of inlay strands influences the structure of the knitted preform by increasing course density, wale density and thickness. This result in the increased anisotropic behaviour of the composite laminate showing increased strength in the course direction and decreased strength in the wale direction. The flexural strength of the knitted preform composites increases in both wale and course directions with the introduction of inlay strands. Laminates from preforms with two inlays exhibit overall improved impact properties whereas those from preforms with one inlay show higher impact damage tolerance index. These observations are explained in terms of the change in fibre architecture brought about by the introduction of the inlay strands.

Keywords: Composites, Glass fibre, Knitting, Mechanical properties, Textile preforms

troduction

he properties of a polymer composite are rmined not only by the kind of matrix and forcing material but also by the geometry of the forcement. Forms of reinforcement can be sified as discrete fibre system, strands/continuous s and textile preforms. Of these three forms of forcement, the textile preforms are widely used as e give better intra- and inter-laminar strength as pared to the other two forms of reinforcement[1]. major textile preform fabrication techniques de weaving, braiding and knitting. Woven rms are made by interlacing strands, braided rms by intertwining strands and knitted preforms nterlooping strands. Both two-dimensional and -dimensional reinforcements can be made with id of these three techniques.

mpared to the woven and braided preforms, the d preforms have superior conformability to licated shapes due to the high deformability cteristics of the knitted structure[1]. It is possible the required final shape of the component using a knitted preform. For instance, the knitted preforms can be deformed to fit the shape of a mould in the RTM process by utilizing their superior deformability. Impact strength of 1×1 rib knitted preform composites is three times higher than that of plain woven preform composites. However, the tensile strength of 1×1 rib knitted preform composites is lower than that of plain woven preform composites[2]. There are many open spaces between the face and back loops of a 1×1 rib knitted preform. These open spaces run along the course direction of the preform. In this study, an attempt has been made to improve the tensile and flexural strengths of the knitted preform composites by filling these open spaces with the introduction of horizontal strands, called as inlay strands, after each course. The specimens have been tested in the tensile, bending and impact modes to study the mechanical properties of the resulting composite laminate.

2 Materials and Methods

2.1 Preparation of Knitted Preforms

Glass rovings were knitted in a V-bed flat knitting machine. The linear density of the E-glass used was 150 tex with zero twist and coated with silane coupling agents. Minimum feed tension was applied during knitting as it has been reported that the tensile

---

nt address: School of Textile & Fibre Engineering, Georgia e of Technology, Atlanta 30318, USA

t address: Department of Textile Technology, Indian e of Technology, New Delhi 110 016, India strength and impact strength of knitted preform composites decrease with the increase in feed tension[2]. The loop efficiency (loop strength divided by tensile strength) of the glass continuous-filament strands decreases with finer knitting needles. The needle hook diameter should be in the range 0.75-1.3 mm for better loop efficiency[3]. Therefore, the traditional 5-needles/in. flat-bed knitting machine was used. The particulars of the machine used for knitting are:

Type	: Flat-bed knitting machine
Gauge	: 5 needles/in.
No. of needles	: 70
Drive	: Hand driven
Feed tension	: Tension only due to the passag of the strand through the guide elements

Three types of knitted preforms were produced as shown in Fig.1. Inlay strands were introduced in the horizontal direction after the completion of each course. The last loops of the preform were held by the two sets of needles, arranged in an inverted 'V' and kept at 90° to each other and at 45° to the horizontal plane. These last loops formed a 'V' in the space created between the two opposing needle beds. The horizontal strand was introduced at the apex of the 'V' section after each course (Fig. 2). The required number of horizontal strands were introduced depending on the sample.

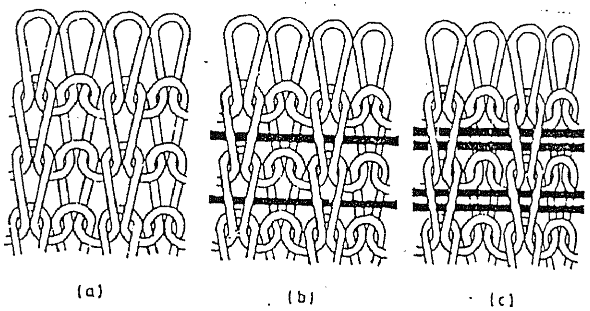

Fig. 1—Structure of 1×1 rib knitted preform with (a) no inlay, (b) one inlay, and (c) two inlays

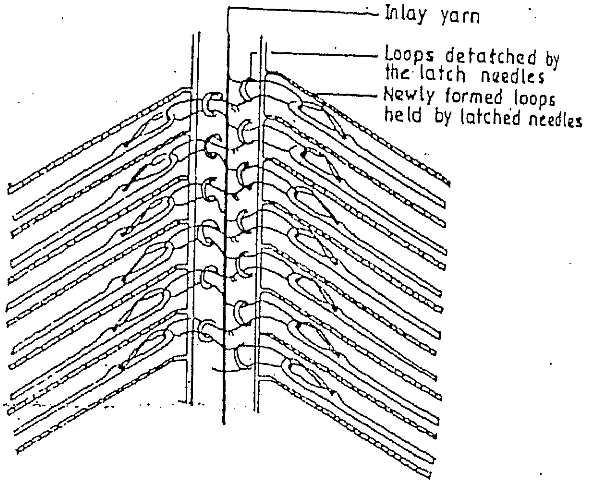

Fig.2—Introduction of inlay strand in a V-bed knitting machine

2.2 Composite Preparation

Vacuum-assisted resin transfer moulding technique was used for the fabrication of knitted preform composites. Two flat moulds (30cm × 30cm) made of chrome-plated hardened steel were used. These were cleaned with acetone and a releasing agent was applied uniformly on the surface of cleaned moulds. A spacer of 15 mm width and 1.5 mm thickness was placed in the female mould. The thickness of the spacer determines the thickness of the laminate.

The knitted preform of 25 cm × 25 cm size was cut and placed in the female mould within the spacer. The male mould was placed over it and clamped tightly so that there was no gap between the spacer and the moulds. The mould was then placed vertically. The mould had an inlet port for the resin introduction and an outlet port for the removal of air. The inlet port was connected to a funnel through a pipe, which was placed at a greater height than the mould. The outlet port was connected to the vacuum pump and the vacuum was applied for 30 min to remove all the air inside the mould.

The required amount of epoxy resin 5052 and hardener 5052 were mixed thoroughly and the resultant mixture was placed in a vacuum chamber to remove all the air bubbles entrapped inside the liquid. Resin was then poured into the funnel connected to the inlet port. Resin flowed into the mould due to gravity and impregnated the preform. The impregnation was facilitated by the application of the vacuum. Total impregnation of the preform was indicated by the flow of the resin through the outlet port. Both inlet and outlet ports were then closed with a pinch cork and the resin was allowed to set inside the mould for 12 h.

2.3 Tests

Impact tests were performed at room temperature using an instrumented Dynatup (Model 8250) drop weight impact tester. Specimen of 90 mm × 90 mm size was clamped horizontally on a rectangular frame and impacted vertically by dropping a hemispherically-nosed (14.3 mm diam.) tup, with impact energy of 25 joules and impact velocity of 3.4 m/s. Tensile test specimens of 150 mm × 25 mm size were prepared. End tabs made of the composite material of size 45 mm × 25 mm were attached at both the sides of the specimen. Flexural test was carried out using a 3-point loading method. Dimensions of the test specimen were 120mm × 12.5 mm and the span length, 90 mm. Both the tensile and flexural tests were carried out in an Instron testing machine (Type 6025)

3 Results and Discussion

3.1 Preform Structure

Introduction of the inlay strands has a significant effect on the structure of the knitted preform (Table 1). Keeping all the parameters constant during knitting, it is found that course density, wale density and the thickness increase with the introduction of the inlay strands. Tension in the inlay strand developed during laying of these strands in the horizontal direction pushed the loops closer to each other, resulting in increase in wale density. Inlay strands caused the front and back loops of 1×1 rib preform to converge around them, causing an increase in thickness and course density of the preform.

3.2 Tensile Strength

The tensile strength of weft knitted preform composite is determined by the fracture strengths of fibre bundles bridging the fracture planes. The fibre bundles bridging the course fracture planes are less than those bridging the wale fracture planes[4]. Hence, the wale specimen displayed higher tensile strength than the course specimen in 1×1 rib knitted composites (Table 1). Introduction of inlay strands increases the tensile properties of knitted preform composites in course direction. Glass fibres give maximum tensile strength when they are loaded along their longitudinal axis. The inlay strand acted as an unidirectionally laid lamina placed between the front and back loops of a 1×1 rib structured composite. This arrangement can be imagined as a three-layered laminate as shown in Fig. 3.

Knitted preforms with two inlays have more number of fibres along the direction of loading. Hence, two-inlays knitted preform composites show higher tensile strength than that of one-inlay knitted preform composite in the course direction. Ordinary 1×1 rib structure does not contain any inlay strand. It can be imagined as a two-layered laminate. Since there is no strand along the direction of loading, it's tensile strength is less. Nevertheless, the introduction of inlay strands decreases the tensile strength of knitted preform composites in wale direction. Both

Table 1—Preform structure and tensile and flexural strength of the knitted preform composites

Preform type	Courses/m	Wales/m	Thickness mm	Weight fraction %	Direction	Tensile strength kg/mm^2	Flexural strength kg/mm^2
1×1 rib with no inlay	552	355	2.6	41.68	Wale	5.146	10.515
					Course	3.952	6.748
1×1 rib with one inlay	749	473	2.8	46.19	Wale	4.806	15.051
					Course	7.618	12.935
1×1 rib with two inlays	788	512	3.9	49.13	Wale	4.175	17.745
					Course	10.677	14.121

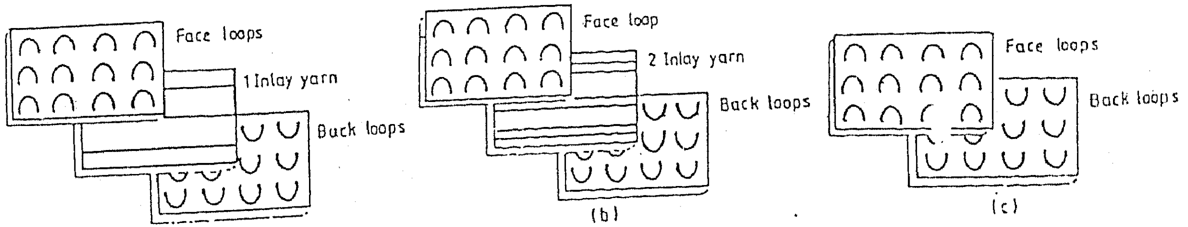

Fig.3—1×1 rib knitted composites treated as a layered laminate: (a) 1×1 rib preform with one inlay, (b) 1×1 rib preform with two inlays and (c) 1×1 rib preform with no inlays

wale density and course density increase in the case of knitted preform with inlay strands. This causes the distortion of the loops. The legs of the loop are somewhat in line with the direction of loading in case of 1×1 rib knitted preform with no inlay. This leads to higher tensile strength along the wale direction.

In the case of knitted preform with inlay strands, the legs of the loop are inclined at an angle with the direction of loading (Fig. 4). Fibres will not be able to contribute much towards the tensile strength and hence, the tensile strength is lower for inlay preforms in wale direction. The loops of the knitted preform with two inlays are more distorted than those of the knitted preform with one inlay. Hence, the tensile strength of two-inlays knitted preform composite is lower than that of one-inlay knitted preform composite in wale direction. By looking at the values of the test results, it may be seen that the laminates from knitted preform with two inlays become more anisotropic than those from the other two knitted preforms. Load-displacement curves of the knitted preform composite are shown in Fig.5.

3.3 Flexural Strength

The flexural strength of 1×1 rib knitted preform composite is higher for the wale specimen than that for the course specimen (Table 1). The reason for this is same as given for tensile strength. The fibre bundles bridging the course fracture planes are less than those bridging the wale fracture planes. Flexural strength increases with the introduction of inlay strands in both course and wale directions. Fibres take up the flexural load and an increase in fibre content in composite will increase the amount of flexural load taken up by the specimen. Introduction of inlay strands increases the volume fraction of the fibres and thus leads to a better flexural strength than that of the knitted preform composite with no inlay. Distortion of loops in the case of knitted preform with inlay strands did not affect the flexural strength of these composites.

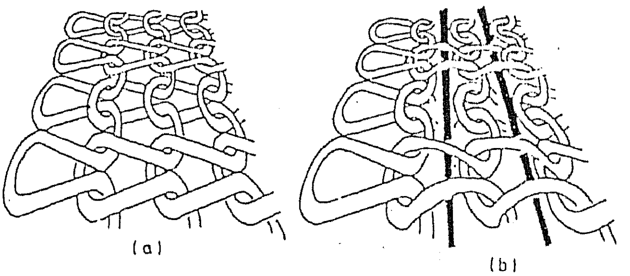

Fig.4—Strand orientation in preforms: (a) 1×1 rib with no inlay, and (b) 1×1 rib with inlay strand

3.4 Impact Strength

The impact involves the relatively high contact forces acting on a small area over a period of short duration, with both elastic and plastic deformation and fracture events occurring. While metals absorb energy in elastic-plastic deformation, the composites generally absorb energy through fracture mechanisms such as delamination, shear cracking and fibre breakage; however, some portion of the energy may be absorbed through the elastic-plastic deformation of the fibre and the matrix. Load/energy *vs* time curves for the knitted preform composites are shown in Fig.6. The characteristic points of these curves are as follows:

The incipient damage point (IDP) is detectable by the first sudden load drop and/or a change of slope in

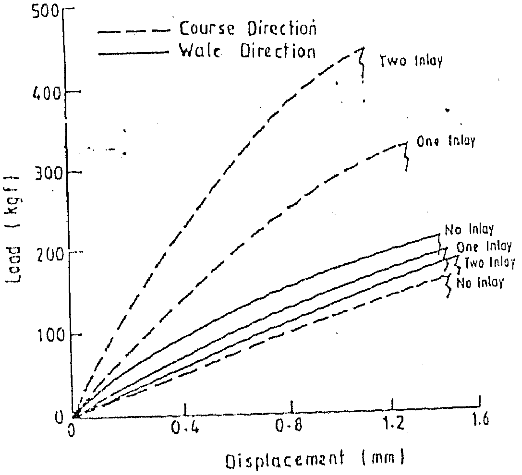

Fig.5—Typical load-displacement curves for the knitted prefor composites

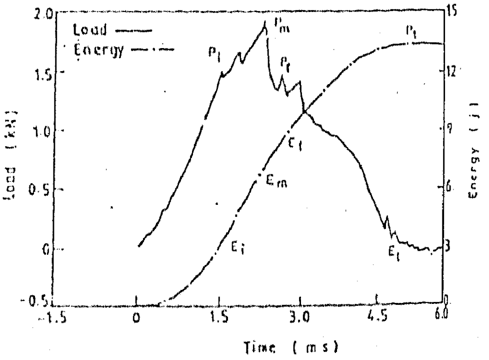

Fig.6—Typical load/energy *vs* time curves for the composite laminates

the ascending portion of the load *vs* time curve. IDP normally is a consequence of internal delamination and/or fibre/matrix interface failure which usually takes place close to the back surface of the impacted panels. The incipient load and energy are denoted by P_i and E_i respectively. The maximum load point (MLP) provides the peak load value that a panel can tolerate under a particular impact event before undergoing major damage. At MLP, a major fibre breakage occurs through the thickness. This breakage normally starts from the back face (the tension side) followed by a penetration on the front face (the compression side) and the damage continues in tension, compression and transverse shear modes. MLP is normally followed by a conspicuous reduction of sample rigidity, signalled in the load *vs* time curve by either a sudden or gradual load drop. A sudden load drop normally occurs in the case of brittle materials, and a gradual load drop normally occurs in the case of ductile materials. The maximum load and the required energy at the maximum load are shown by P_m and E_m respectively.

At the failure point (FP), the panel loses its structural integrity, fails completely and can sustain no more load. The failure point is the point where the load starts to drop to the zero load level with a constant slope. The failure load and the corresponding energy at FP are denoted by P_f and E_f respectively. The total point (TP) is the point where the impact event ends, the load returns to zero and energy has a constant value. The load and energy at this point are shown by P_t and E_t respectively. E_t denotes the total energy absorbed by the panel. The difference between E_t and E_m (absorbed energy to maximum load) is a measure of the energy required to propagate the damage (delamination, fibre breakage, matrix cracking, interfacial failure and fibre pullout) and is denoted by E_p (i.e. $E_p=E_t-E_m$).

Studies have revealed that it is the nature of application area for the materials that determines a particular failure criterion[5]. If a composite specimen absorbs lower total energy and the energy absorbed at the incipient damage point as well as the absorbed energy to the maximum load is high, it leaves a lower energy value for the damage propagation which, in turn, causes a lesser extent of damage. Residual strength for these specimens will be high. Conversely, if a composite specimen absorbs a higher total energy, then most of this energy will be used to create a larger and denser damage zone, which directly reduces the residual strength.

If the material is to be used in a leak-tight structure where the existence of even a small crack is critical, then a material with higher E_i is desirable. If the material is to be used in a primary structure (e.g. load-bearing solid panels) where a high residual strength and/or stiffness is required, then a material which can absorb a great deal of energy in elastic-plastic form and spend less energy for damage propagation is desirable, i.e a material with high E_m as well as relative high E_t. If the material is to be used in a secondary structure (such as face sheets over a honey comb core) where a high resistance to through-penetration is required, then a material that can absorb a great deal of total energy (E_t) through elastic-plastic deformation as well as the damage creation and propagation process is desirable. It is found that 1×1 rib with two inlays has all the characteristic parameters of the dynamic response curves (E_i, E_m or E_t) better than those of any other preform (Fig.7). The 1×1 rib with two inlays has overall better impact properties and it can be used for a wide range of applications.

Due to the significant compressive strength reduction of the impacted composites, the impact damage tolerance concept, a measure of compression after impact, has become important for the evaluation of composites in structural applications. A damage tolerant material exhibits a relatively high total energy, a higher portion of which is consumed through the elastic-plastic deformation (higher E_m) and a lower portion through the creation and more importantly, propagation of damage (lower E_p). For

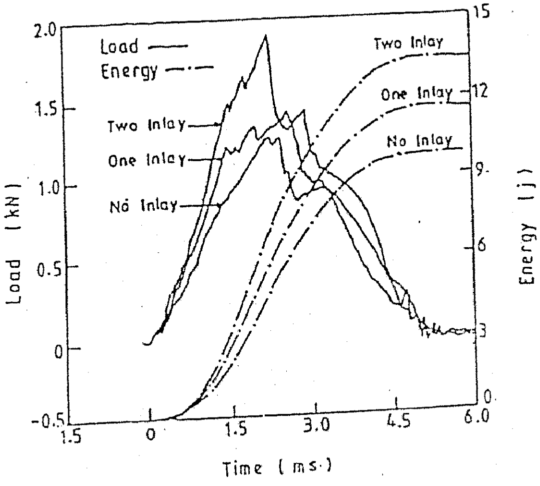

Fig.7—Comparison of load/energy *vs* time curves for knitted preform laminates

Table 2—Impact properties of composite laminates

Preform type	IDP		MLP		FP		TP		DTI
	Load N	Energy joules	Load N	Energy joules	Load N	Energy joules	Load N	Energy joules	
1×1 rib with no inlay	0.89	2.03	1.26	4.76	0.84	6.433	—	9.76	0.95
1×1 rib with one inlay	1.17	2.80	1.35	6.51	0.97	8.701	—	11.57	1.29
1×1 rib with two inlays	1.47	3.25	1.90	7.02	1.42	8.526	—	13.41	1.10

IDP— Incipient damage point; MLP—Maximum load point; FP—Failure point; TP—Total point; and DTI — Damage tolerance index.

this purpose, the damage tolerance index (DTI), as defined below, is used:

$$\mathrm{DTI} = E_m / E_p$$

The 1×1 rib preform with one inlay has higher DTI than any other preform (Table 2). This means that 1×1 rib preform with one inlay has optimum fraction of inlay strands which results in optimal fibre architecture as far as the damage tolerance is concerned.

4 Conclusion

Introduction of inlay strands affects the structure of the 1×1 rib knitted preform by increasing course density, wale density and thickness of the preform. Moreover, with the introduction of inlay strands, the tensile strength of the knitted preform increases in course direction due to the increased contribution from the inlay strands. There is a drop in the strength along the wale direction due to the increased strand disorientation. Composite laminates from knitted preforms with two inlays are more anisotropic than those from the knitted preform with one and no inlay. Flexural strength of the 1×1 rib preform composite increases in both course and wale directions with the introduction of inlay strands which is mainly due to the increased fibre volume fraction. Composite laminates from knitted preforms with inlays demonstrate better properties during impact testing due to the change in the fibre architecture brought by the introduction of inlay strands.

References

1 Wei Liang Wu, Hiroyuki Hamada, & Zenichiro Maekawa, *J Text Inst*, 85 (1994) 198.

2 Chou Shen & Chi-Jen Wu, *J Reinf Plast Compos*, 2 (1992) 1239.

3 Lau K W & Dias T, *J Text Inst*, 85 (1994) 173.

4 Ramakrishna S, Cuong N K & Hamada H, *J Reinf Plast Compos*, 16 (1997) 946.

5 Ghasemi Nejhad M N & Majidi Parvizi A, *Composites*, 21 (1990) 155.