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Weight reduction using composites has gained increasing attention in recent times. In this study, pultruded composite pins (unconfined and confined) were manufactured and tested by using a custom double shear testing fixture. Different configurations were applied for confinement of the composite pins, including weft-knitted fabrics (plain, 1 × 1 rib, and Milano), woven fabrics and E-glass 130 tex fibers/adhesive cloth. They were externally wrapped and bonded to the unconfined composite pins. In each case, five identical specimens were tested, and shear strength data were analyzed by using two-parameter Weibull statistics. The results showed that the maximum shear strength took its highest value in the unconfined case for both average values of the test results and for 99% reliability under Weibull distribution. The confinement had a negative effect on the average shear strength of the unconfined pins. It was also seen that the 99% reliability values of shear strength were approximately equivalent to the 0.7 average value of the shear strength.

Keywords: fabrics/textiles; shear strength; pultrusion; Weibull distribution

1. Introduction

The application of fiber composites has shown a tremendous growth in many fields ranging from trivial, industrial products such as boxes and covers produced in enormous numbers each day, to pipelines and crucial, load bearing parts of large structures. Some important reasons for this popularity are as follows: their high strength (and stiffness) to weight ratio; the possibility of controlling the anisotropy; and the fact that the fiber composites are resistant to corrosion. The analysis of fiber-reinforced composite materials production processes over the past years shows that pultrusion is gaining an ever-increasing share of the market. Pultrusion is one of the fastest and most cost-effective processes, by which composites can be manufactured. Recently, the use of pultruded composites has included a number of new' structural applications because these composite structures also have desirable properties in corrosive and chemical environments. Various cross-sectional shapes with continuous length can be produced in a single-step process. For all of these reasons, pultruded composite structures are seen as

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being more and more competitive with other traditional materials such as steel and aluminum.[1,2]

There are generally two kinds of joining methods for composite structures: (1) mechanical fastening and (2) adhesive bonding. Although adhesive bonding has many advantages over traditional mechanically fastened joints in that they have fewer sources of stress concentrations, more uniform distribution of loads, and better fatigue properties, in some cases, joints are joined mechanically by using steel fasteners (nuts and bolts, screws, pins, and rivets). Undoubtedly, the fasteners are responsible for increasing the weight of the overall assembly.[3]

Nowadays, textile composites are increasingly being used in advanced structures in aerospace, automobile, and marine industries. The application of textile composites in engineering structures has been driven by various attractive aspects such as ease of handling, high adaptability, light weight, and high specific stiffness. Textile composites are generally classified into three basic categories according to the textile forming techniques used for composite reinforcement: (i) woven fabrics, (ii) knitted fabrics, and (iii) braided fabrics. When comparing with other conventional composites, knitted fabrics are in a situation between continuous fiber mats and woven or braided fabrics. The stiffness and strength of the knitted fabrics are higher than fiber mat composites, but somewhat lower than woven fabrics. Additionally, knitted fabric composites are usually more isotropic than woven fabric composites, and one of the outstanding features is the interlaminar fracture toughness.[4–6]

In this study, the ability of pultruded composite pins (PCP) to withstand shear stress was investigated. PCP (with/without confinement) were manufactured and tested at room temperature by using a custom double shear testing fixture. As stated earlier, textile composites have become popular nowadays; therefore, confinement configurations were selected as follows: weft-knitted fabrics (plain, 1 × 1 rib, and Milano), woven fabrics, and E-glass 130 tex fibers/adhesive cloth. The purpose of the confinement is to improve strength in circumferential direction. There are no experimental data that would investigate this case in the literature. With this study, the authors attempted to fill this void in the literature.

2. Experimental program

2.1. Materials

2.1.1. E-glass fibers

Tex is a metric unit used in the textile industry to measure the density of a single fiber of yarn. One tex equals a density of one gram per kilometer of length. In this study, the glass fibers were consisted of direct rovings in 130 and 2400 tex. 130 Tex type E-glass fibers were supplied from Pul-Tech FRP Company and are used as delivered.

2.1.2. Pultruded composites

The core material was E-glass-reinforced polyester composites, supplied as pultruded rod (diameter 16 mm × height 4200 mm) by Pul-Tech FRP Company. They all contained unidirectionally aligned E glass 2400 tex rovings, with a volume fraction of about 60%. The matrix material was isophthalic polyester.

Static tensile tests were carried out to determine the mechanical properties of the pultruded composite. Six repeated tests were executed on rectangular samples

(3 mm × 15 mm × 300 mm) according to ASTM D3039.[7] The displacement controlled test was conducted at a crosshead speed of 2 mm/min. All specimens exhibited a linear behavior up to failure. Table 1 shows the mechanical properties of the pultruded composite.

2.1.3. *Textile fabrics*

Woven and selected weft-knitted glass fabrics, viz., plain knit, rib, and Milano were manufactured as confinement materials. Their appearance and schematic diagrams are shown in Figure 1. The weft-knitted fabrics were constructed on a seven-gauge flatbed knitting machine from 130 tex glass yarn with a slight twisting under the same knitting conditions. As the matrix material, epoxy CY 225 and hardener HY 225 are mixed in the mass ratio at 100:80. The fiber volume fraction was approximately 55%. The physical properties of each knitted fabric are summarized in Table 2. The last type of confinement fabric was the plain weave (woven) fabric with a weight of 320 g/m^2. The fiber volume fraction was 50%. The mechanical properties of the textile fabrics were determined in accordance with ASTM standards [8–10] and given in Table 3.

2.1.4. *Adhesive*

The adhesive used for confinement was prepared by the following steps: Isophthalic polyester resin was put into a container, and cobalt(II) naphthenate promoters added to this container in the ratio of 0.4% by weight in order to improve the cure rate of unsaturated polyester resin. The resin was left undisturbed approximately 30 min after adding the promoter. Methyl ethyl ketone peroxide (MEKP) activator which initiated the polymerization of polyester resin added to polyester/cobalt mixture by using a syringe in the ratio of 2% by weight. Due to the very fast cure speed, small amounts of the adhesive were prepared for each application.

2.2. Specimen preparation

Thirty PCP were manufactured and grouped into six groups, *viz,. A, B, C, D, E,* and *F,* each consisting of five specimens.

Group A specimens were unconfined and used as a reference. They were directly manufactured by cutting a pultruded composite rod into five equal parts each 16 mm in diameter and 70 mm in height by using a rotary-CNC machine.

For each specimen of groups *B*, *C*, *D,* and *E*, the diameter of pultruded core rod was 14 mm. They were confined PCP by textile fabrics, and they were fabricated by the following steps: Firstly, the rod diameter was reduced from 16 to 14 mm. Prepared adhesive was applied to textile fabric surface by using a roller. Then, the textile fabric was wrapped around external surface of the composite rod. This process was repeated several times until the total diameter reached 18 mm. Then, the rod was tightened with a steel wire to prevent separation of the fabric. In order to prevent the release of the

Table 1. Experimental results of static tests*.

Average failure stress (MPa)	Average failure strain	Average Young's modulus (MPa)
725 (51)	0.0148 (0.0006)	53 (1.5)

*The values in parentheses ( ) represent ± standard deviation.

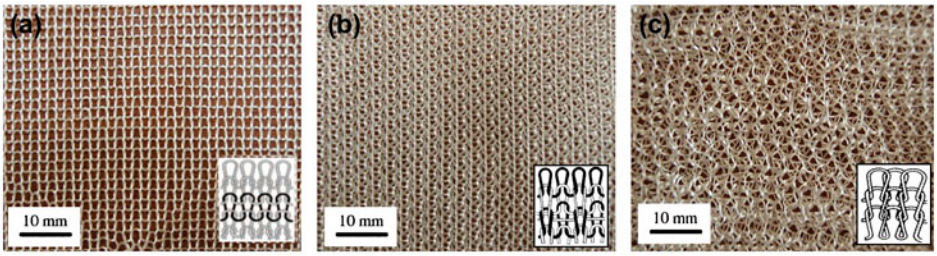

Figure 1. The photograph and the schematic diagram of the weft-knitted fabrics: (a) plain knit, (b) Milano, and (c) 1 × 1 rib.

Table 2. Physical properties of the knitted fabrics.

Fabric type	Area density (gr/m^2)	Course Density (Course/cm)	Wale Density (wale/cm)
Plain	328	5	3.5
1 × 1 Rib	345	4	3.5
Milano	385	5	3.5

Table 3. Mechanical properties of composites*.

Fabric type	E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12} (-)	X_t (MPa)	Y_t (MPa)	X_c (MPa)	Y_c (MPa)	S_i (MPa)	S_{12} (MPa)
Woven	30.76	25.17	3.32	0.21	410.95	398.14	128.90	86.86	14.70	66.49
Plain	7.91	4.22	1.60	0.17	73.21	32.88	17.97	14.91	10.2	29.45
Rib	14.06	8.74	14.30	0.19	97.91	55.87	38.76	23.72	26.32	69.57
Milano	12.47	8.17	6.81	0.18	85.87	78.52	32.94	30.70	15.80	59.35

*1 – fibres direction, 2 – transverse direction, X_t – longitudinal tensile strength, Y_t – transverse tensile strength, X_c – longitudinal compressive strength, Y_c – transverse compressive strength S_i – interlaminar shear strength, S_{12} – shear strength.

steel wire, a 3 kg mass is attached to its end during the tightening process. They left undisturbed until the full cure of the adhesive about 24 h. The steel wire was removed, and the rod diameter was reduced from 18 to 16 mm and cut into five specimens.

The pultruded core diameter was 14 mm for Group F specimens. In order to manufacture Group *F* specimens, the composite rod was mounted on a lathe machine then continuous E-glass 130 tex fibers were wrapped around the rod until its total diameter reached 18 mm. The rod was tightened with a steel wire (a 3 kg mass attached to the its end) and left undisturbed until the full cure of the adhesive. The steel wire was removed and the composite rod was cut into desired dimensions (diameter 16 mm × height 70 mm). Definition and details are given in Table 4. Figure 2 shows photographs of each specimen.

2.3. Testing procedure

Custom testing fixture used in double shear testing of test specimens is shown in Figure 3. Five experiments were performed for each group. Displacements and loads

Table 4. Details and definition of the PCP that was tested.

Group name	Diameter (mm)*	Confinement condition
A	16	No-wrapping (reference)
B	16	Woven fabric
C	16	Plain
D	16	Rib
E	16	Milano
F	16	E-glass 130 tex/adhesive

*For each specimen of groups B, C, D, E and F, the pultruded core rod diameter was 14 mm.

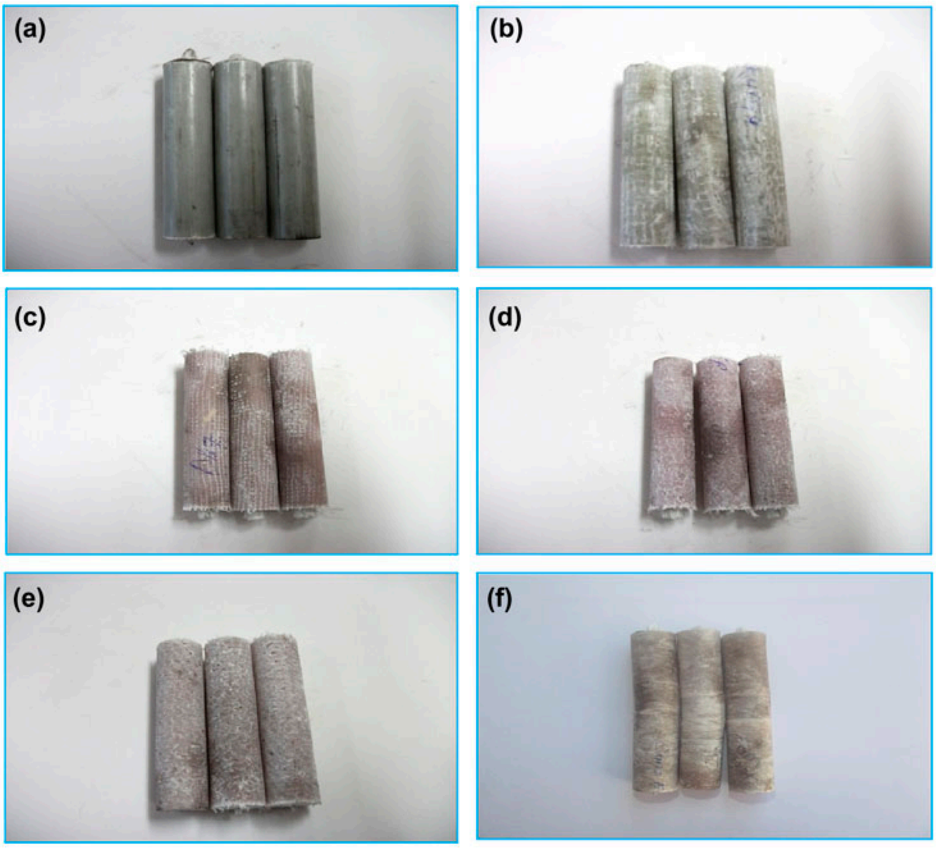

Figure 2. The photographs of the specimens; (a) Group A, (b) Group B, (c) Group C, (d) Group D, (e) Group E, and (f) Group F.

were automatically recorded using a computer system. Tests were conducted under laboratory conditions. The temperature in the testing laboratory was 20 ± 3 °C. No washer or lateral supports were used in order to represent a worst case scenario for in-service conditions. Each specimen was inserted in the hole in the shear test fixture. Tensile load was gradually applied to the upper crosshead with a speed of 1.5 mm/min. The experiments were performed until ultimate failure, and the test results were then used

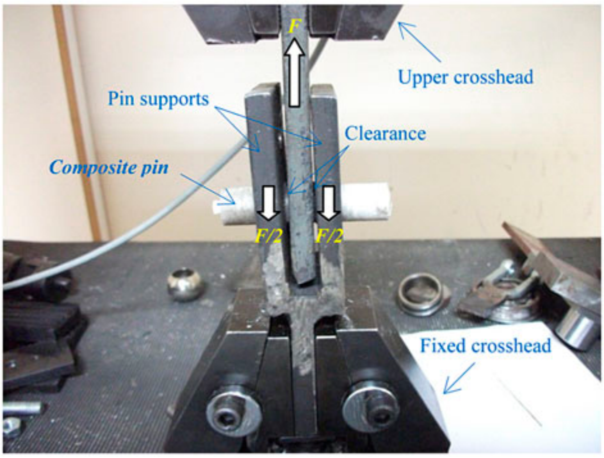

Figure 3. A photograph of the specimen under shear testing.

to calculate the average shear strength on the cross-section of the pin. After failure, photographs were taken and the specimen was inspected to determine the mode of failure.

3. Statistical analysis

3.1. Weibull distribution

Weibull distribution is used to model extreme values such as failure times and fracture strength. Two popular forms of this distribution are two- and three-parameter Weibull distributions. The (cumulative) distribution function of the three-parameter Weibull distribution is given as follows [11]

$$F(x;a,b,c) = 1 - \exp\left(-\left(\frac{x-a}{b}\right)^c\right), \quad a \geq 0,\ b \geq 0,\ c \geq 0 \tag{1}$$

where a, b, and c are the location, scale, and shape parameters, respectively. When $a = 0$ in Equation (1) the distribution function of the two-parameter Weibull distribution is obtained. The three-parameter Weibull distribution is suitable for situations, in which an extreme value cannot take values less than a. In this study, the two-parameter Weibull distribution was considered. The distribution function can be written as follows [12]:

$$F(x;b,c) = 1 - \exp\left(-\left(\frac{x}{b}\right)^c\right), \quad b \geq 0,\ c \geq 0 \tag{2}$$

In the context of this study, $F(x;b,c)$ represents the probability that the failure load of the specimen is equal to or less than x. Using the equality $F(x;b,c) + R(x;b,c) = 1$, the reliability $R(x;\ b,\ c)$, that is, the probability that the failure load is at least x, is defined as [13]

$$R(x;b,c) = \exp\left(-\left(\frac{x}{b}\right)^c\right), \quad b \geq 0,\ c \geq 0. \tag{3}$$

The parameters b and c of the distribution function $F(x;b,c)$ can be estimated by three different methods such as linear regression, method of maximum likelihood, and method of moments. Among these methods, use of linear regression goes back to the days when computers were not available: The linear regression line was fitted manually with the help of Weibull graph papers. Linear regression is still common among practitioners, and it was used for parameter estimation in this study.

3.2. Method of linear regression

This method is based on transforming Equation (2) into $1 - F(x; b, c) = \exp\left(-\left(\frac{x}{b}\right)^c\right)$ and taking double logarithms of both sides. Hence, a linear regression model in the form $Y = m\,X + r$ is obtained:

$$\ln\left[\ln\left(\frac{1}{1 - F(x; b, c)}\right)\right] = c\ln(x) - c\ln(b) \tag{4}$$

$F(x;b,c)$ is an unknown function, and therefore, it is estimated from observed values: n is the number of observations from smallest to largest, and let $x_{(i)}$ denote the ith smallest observation ($i = 1$ corresponds to the smallest and $i = n$ corresponds to the largest). Then, a good estimator of $F(x_{(i)};b,c)$ is the median rank of $x_{(i)}$ [14]:

$$\hat{F}(x_{(i)}; b, c) = \frac{i - 0.3}{(n + 0.4)} \tag{5}$$

When linear regression, based on least squares minimization, is applied to the paired values $(X, Y) = \left(\ln(x_{(i)}), \ln\left[\ln\left(\frac{1}{1-\hat{F}(x_{(i)};b,c)}\right)\right]\right)$ for the model in Equation (4), the parameter estimates for b and c are obtained.

4. Results and discussion

4.1. Experimental results

Load-displacement curves of the test specimens are shown in Figure 4. Each curve was an average of five tested specimens in the same group. Each group of tests showed

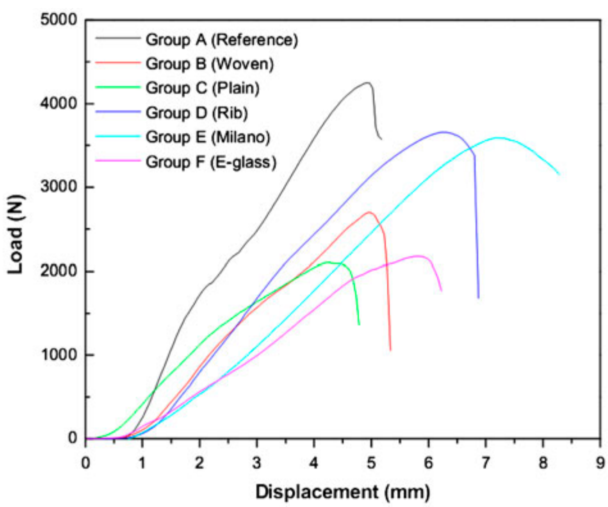

Figure 4. Load-displacement curves of PCP wrapped in various configurations.

good repeatability in terms of slope and delay in load take-up. The curves exhibited pseudo-linear behavior at the early stages of loading and then transformed to nonlinear. At this stage, we started to hear first noises in the form of snapping sounds from the specimens. Some slight drops were observed in the curves due to small cracking in the specimens. After some displacement, complete failure of the specimens was occurred. Results summary of shear tests is shown in Table 5. The average shear strength on the cross-section of the pins was obtained by dividing the total shear force V by the area A of cross section on which it acts. Since the pins were in double shear, the total shear force V was equal to half of the average failure load of each group. As shown in the table, the highest shear strength was recorded with specimen of Group *A* (10.31 MPa) while Group *C* (5.10 MPa) had the lowest. Group C showed the lowest strength because shear stresses are mainly responsible for failure of test specimens and shear strength (S_{12}) value of plain knit is the lowest compared to the other fabrics as shown in Table 3. There were significant differences between groups *A*, *D,* and *E* vs. groups

Table 5. Experimental results of shear tests.

Group name	Number of specimen	Average failure load (N)	Average shear strength (MPa)	Average failure displacement (mm)
A	5	4146.15	10.31	4.9
B	5	2838.53	7.06	5.0
C	5	2051.35	5.10	4.3
D	5	3546.01	8.81	6.4
E	5	3483.53	8.66	7.3
F	5	2160.56	5.37	5.9

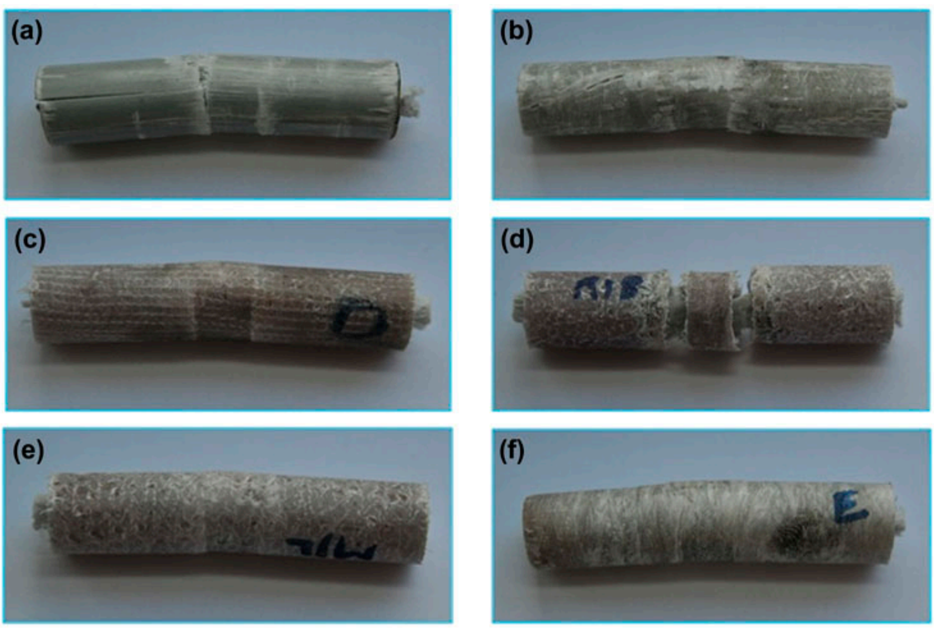

Figure 5. Photographs of each specimen after failure: (a) Group A, (b) Group B, (c) Group C, (d) Group D, (e) Group E, and (f) Group F specimen.

B, *C,* and *F*. Additionally, there was no significant difference between groups *D* and *E* due to the similarity of the knitting method. In all cases, the confinement process caused a reduction in shear strength. However, the maximum crosshead displacement values varied substantially, being highest for Group *E* and lowest for Group *C*. This is probably due to the difference between knitting structures. The photographs of the specimens after the test are shown in Figure 5. All specimens were experienced shear failures at the contact surface of the connected rigid plates due to the maximum shear force exceeded the capacity of the specimens. At the early stages of loading, the bearing occurred in the contact area of the wrap surface and the fixture. The confinement materials had a negative effect on the average shear strength because most of the shear stress developed in the pins was carried by longitudinal fibers in the specimens. The shear tests were then continued in order to observe cross-section of the pins until complete failure reached.

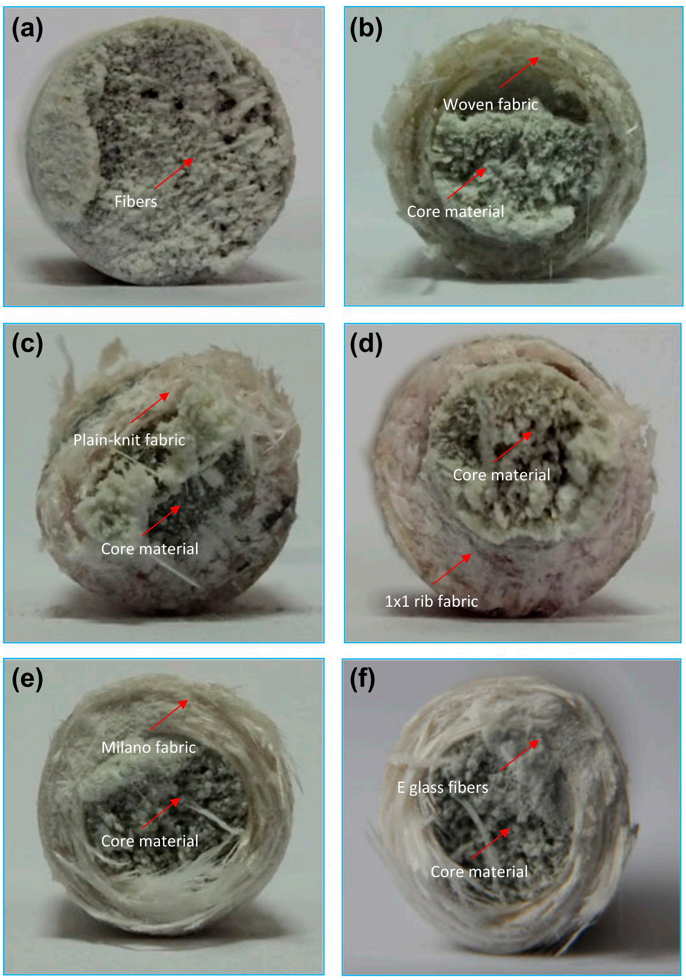

Figure 6. Photographs of the cross-sectional top view of (a) Group A, (b) Group B, (c) Group C, (d) Group D, (e) Group E and (f) Group F specimen.

It is also seen from Figures 4 and 5(e), and (f) the confined pins are relatively ductile. This is because the core material was composed of 60% polyester and 40% calcium carbonate (except fiber fraction). The adhesive used for the manufacture of confined pins was more ductile than the core material. The cross-sectional top views of the pins are shown in Figure 6.

4.2. Weibull distribution

Figure 7 shows regression lines for each group. Although the first point does not appear to fit the line well, this is an expected situation in the method of linear regression; among consecutive ($Y(i)$, $Y(i+1)$) pairs, ($Y(1)$, $Y(2)$) has the largest absolute difference.

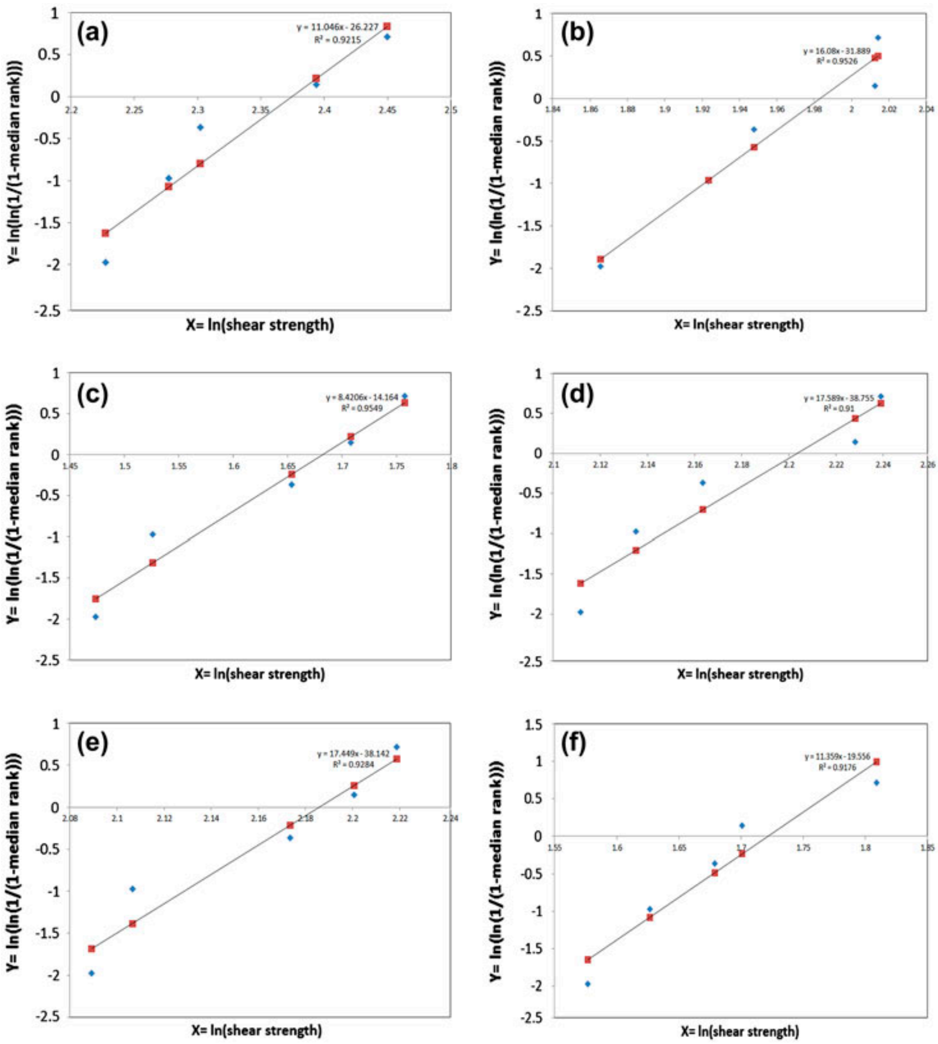

Figure 7. Regression lines for each group; (a) Group A, (b) Group B, (c) Group C, (d) Group D, (e) Group E, and (f) Group F.

Table 6. Comparison of average shear strength and 99% reliability strength.

Group name	Average shear strength (MPa)	Weibull Distribution (%99 reliability)
A	10.31	7.08
B	7.06	5.45
C	5.10	3.11
D	8.81	6.97
E	8.66	6.84
F	5.37	3.73

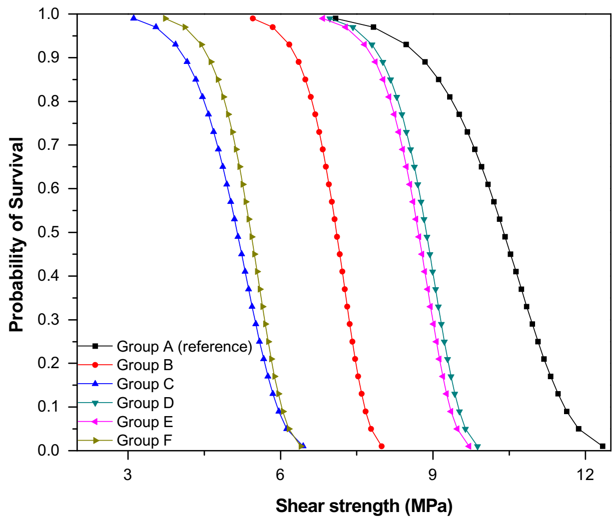

Figure 8. Weibull distribution plot for probability of failure at given stress (MPa) for groups A, B, C, D, E, and F specimens.

Table 6 shows the results of the Weibull analysis. As shown in the table, the highest 99% reliability strength value of 7.08 MPa was obtained for Group A specimens. The lowest 99% reliability strength was 3.11 MPa (Group C). It is also seen that the shear strength values obtained from the Weibull analysis were approximately 30% lower than those obtained from the experimental data.

The Weibull analysis for shear strength is given in Figure 8. As shown in the figure, shape parameter of Group A is smaller than those of groups B, C, D, E, and F. It means that scattering in the values of failure load was reduced by the confinement. The reason for the scattering of the experimental results is not precisely known. However, this can be best explained by the fact that the damage was in the form of transverse matrix cracking for Group A specimens. The other group of specimens failed more uniformly due to fiber breakage therefore scattered less than others.

5. Concluding remarks

In this study, the ability of *PCP* to withstand shear force was investigated experimentally and statically. Two groups of *PCP* were investigated: (i) unconfined

PCP and (ii) confined *PCP*. Three different confinement schemes were considered: E-glass 130 tex fibers, woven, and knitted fabrics. The knitted fabric configurations were selected as 'plain,' '1 x 1 rib,' and 'Milano'. The tests were carried out by using a custom testing fixture. The experimental results were statically analyzed by using the two-parameter Weibull distribution function. From the results, the following conclusions can be drawn:

- The PCP with no confinement (Group A) possessed the highest shear strength because most of the shear stress was carried by longitudinal fibers in the specimens. The PCP confined by plain knit (Group C) had the lowest average shear strength.
- There was no significant difference between groups *D* and *E* due to the similarity of the knitting method.
- Maximum failure displacement was observed for the composite pins confined by Milano fabric (Group E).
- The confinement had a negative effect on the average shear strength of the unconfined pins.
- The shear strength values obtained from the Weibull analysis were approximately 30% lower than those obtained from the experimental data for all cases.

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