General paper

Numerical Studies on Elastic Properties and Failure Mechanisms of Knit Fabric Composites

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Abstract: This paper describes elastic behavior and failure mechanisms of plain-knit fabric composites. A single-ply glass-fiber knit fabric impregnated with epoxy resin was used to fabricate composite specimens. Tensile tests were then carried out in two directions: the wale and the course directions of the fabric. During the test, the fracture behavior of the composite specimen was identified by a video camera which caught the loop images from the beginning to their failure. Tensile properties were also experimentally determined. Furthermore, a three-dimensional (3-D) finite element model of a knitted loop was proposed for prediction of tensile moduli as well as failure mechanisms of the plain-knit fabric composite. The validation of the loop model was estimated by comparison of the experimental results with the predicted ones.

Key words: *Knitted loop, Plain knit fabric composites, 3-D numerical model, Failure mechanisms*

1. INTRODUCTION

Composites based on knitted fabrics as reinforcements have some advantages over woven and braided composites owing to their high drape-ability and possibility of forming a complicated shape with a reduced number of processing steps. The loose structure of knitted fabrics is mainly deformed by gliding of loops over each other. Therefore flexible composites with a much larger usable range of deformation than conventional laminated composites can be achieved by combination of an elastomeric resin with the knitted fabric [1,2]. Moreover, the knitted fabric was reinforced with matrix in composites; the matrix prevents the movement of the loops, so that the fibers are loaded. This enhances stiffness of the materials dramatically.

In spite of these advantages, knitted fabric composites have not been widely used. The main reason is that they have lower in-plane mechanical properties than the conventional composites owing to their low fiber volume fraction and the loop configuration of fibers. The partially out-of-plane oriented fibers decrease the in-plane stiffness. The curvature of the loops also brings high concentrated stress, which promotes damage development and considerably decreases strength.

So far, many research works which concentrated on improving mechanical properties of warp and weft knit fabric reinforced composites are available in the literature [3-9]. However, only a limited number of them have reported on the modeling of knitted fabric-reinforced composites.

Rudd et al. [10] performed experimental and theoretical studies on the elastic and failure properties of glass polyester weft knit laminates. The comparison between the strength of the weft knit composite and the strength of a continuous-filament random-mat reinforced

composite was also studied. The stiffness model was proposed based on the well known rule-of-mixtures. The predicted elastic moduli of the plain-knit fabric composite were higher than experimental values.

Ko et al. [8] investigated the structure and properties of multilayers and multidirectional warp knit fabric reinforced composites. The fabric geometry model has been developed based on the unit cell concept and the modified laminate theory for predicting the tensile properties of warp knit-fabric composites. The comparison of theoretical and experimental results showed that the fabric geometrical model was the reasonable model for the prediction of the stress-strain behavior of the warp knit fabric composite. Gommers et al. [9] extended the same concept to the composites reinforced by conventional warp knit fabrics. Some models were presented to calculate their elastic modulus.

Lately, Ruan et al. [10] determined the elastic behavior of plain and rib-stitch fabric composites. Geometric models for both composites were proposed and modeling of the elastic behavior was conducted by using the averaging method. However this study is also limited to the prediction of the elastic behavior.

Fig.1. Optical photograph and schematic illustration of the plain knit fabric.

In this study, therefore, a three-dimensional (3D) finite element model (FEM) constructed from the plain knit structure was proposed for predicting the elastic behavior and tensile failure mechanisms of the single-ply plain knit fabric reinforced with epoxy composites. The comparison of the experimental results with the pre-dictions validated the knit model. The applicability and limitation of the knit loop model were also discussed.

2. EXPERIMENTAL STUDIES

2.1. Fabrication of Plain Knit Fabric Composites

Plain fabrics made from glass fiber yarn (ECD 450 1/2 4-45Y-23) were produced by a flat knitting machine with the machine gauge of 6. The fabric and epoxy resins (Epikote-828) were used as the reinforcements and the matrix, respectively.

During knitting, spring extension force was adjusted to a minimum; this reduced the breaking of glass fiber's filaments. Figure 1 illustrates the optical photograph and the schematic illustration of the plain knit glass-fiber fabric.

Composite laminates were fabricated based on the combination of the single-ply knit fabric with the epoxy resin. To improve the adhesion between glass fiber bundles and the matrix resin, the fabric was chemically treated with amino-silane coupling agent prior to resin impregnation. It was then wetted in a mixture of the epoxy resin and ($C_6H_{18}N_4$) hardener triethylenetetramine. During curing time, a high pressure of 7.5MPa was applied to the laminate to produce the composite with thinner resin surface layers.

Composite specimens of 200mm length, 20mm width and 0.6mm thickness were prepared by cutting a panel parallel to the wale and course directions of the fabric. Aluminum end tabs of 50mm length were glued to the both ends of each specimen to prevent the failure of the specimen at gripped places.

2.2. Tensile Tests

All in-plane elastic constants of the composite were determined experimentally. Young's moduli as well as Poisson's ratios were determined by tensile tests carried out for composite and pure matrix specimens. A bi-axial strain gauge was stuck onto the surface at the middle of the specimen's gauge length to measure strains in the wale and course directions. The specimen was tested at the crosshead speed of 1 mm/min on the testing machine (Instron type 4206).

A low crosshead speed of 0.1 mm/min was also set up to well pursue fracture process of the composite specimen during tensile tests. Illuminated with high intensive light, knitted loops and their fracture process were clearly observed owing to the transparent matrix resin. The damage progression of specimens was recorded by a video camera (PIAS model CB400A). The fracture surfaces of the specimen were studied using an optical microscope and a scanning electronic microscope (SEM).

3. FINITE ELEMENT MODEL FOR PREDICTION OF TENSILE PROPERTIES

A loop connected with the other adjacent loops at four interlocking points in three-dimensional direction was considered as a unit cell of the plain knit fabric (shown in Fig.2), and repeating the unit cell, complete plain knit structure can be generated. A 3-D numerical model of the plain knit fabric composite was, therefore, proposed based on this unit cell (Fig.3).

In the unit cell, thick lines represent the fiber bundles while thin lines denote resin elements. The fiber bundles impregnated with resins are regarded as unidirectional rods, and represented by the 3-D shaped beam elements with two end nodes (shown in Fig.3).

The surface resin elements are described as rectangular cross-sectional shaped beam elements oriented in 3-D space. The total of the half distances (w) between the adjacent nodes (Fig.3) is taken as the width of each rectangular resin element.

Fig.2. Unit cell of the plain-knit fabric.

Fig.3. Three-dimensional numerical model of the plain knit fabric composite.

The crossover of fiber elements at the interlocking region can be represented by two kinds of crossovers. Crossover A represents crossing of fiber bundles of the upper and bottom loops while crossover B is formed by adjacent needle and sinker loops. For transmitting the applied force from one fiber element to another, resin elements are set up at the crossovers. The cross-sectional shapes of the resin elements at the crossovers are assumed to be circular (shown in Fig.3). Based on microscopic observation of the fiber bundles in composite laminate's sections, the diameter of the fiber beam elements was estimated as 0.38 mm and the diameters of the resin elements at the crossover A and B were 0.43 mm and 0.49 mm, respectively.

The following assumptions were used in the numerical analysis:

- 1) Fiber bundles have the same cross-section throughout the knit loop.
- 2) The heads of the needle loops and the sinker loop are either circular or elliptical in shape. However, in this model the fiber bundles are assumed to be straight lines connected at different angles.

Mechanical properties of the resin and fiber elements were calculated using the rule of mixture and they are summarized in the Table 1.

The nonlinear analysis of the tensile behavior of the knit fabric composite was carried out using incremental displacement that was subjected to one end of the model while the other end was considered to be fixed. The incremental displacement at each time was 0.03 mm. When the stress of the elements reached their critical strength, the failure of them was assumed. The knit fabric composite was regarded as being failed when the failure of any fiber element occurred.

4. RESULTS AND DISCUSSION

4.1. Tensile Modulus

Typical stress-strain curves obtained from the tensile tests are shown in Fig.4. The Young's modulus was determined as a tangent modulus at a longitudinal strain of 0.1% on the stress-strain curve. Poisson's ratio was also calculated at 0.1% longitudinal strain. In general, the wale direction displays higher elastic modulus than course direction.

The 3-D FEM was used to calculate the elastic moduli of the composite in which the fiber yarn has out-

Table 1. Material constants of fiber and matrix elements.

Element	Elastic Modulus E , GPa	Strength σ , MPa	Poisson's ratio, ν
Glass fiber bundles	34	657	0.26
Epoxy matrix	3.6	47	0.35

Fig.4. Typical stress-strain curves obtained from the tensile test

of-plane orientation. Table 2 summarizes the tensile moduli obtained from FEM and experiments in both the wale and course directions. The validity of the numerical model was presented by comparing the predicted moduli and with the experimental results.

Similar to the experimental results, the predicted values indicated that the elastic modulus was higher in the wale direction than that in the course direction. This is due to the higher proportion of fiber oriented in the wale than in the course direction. Table 2 demonstrates that the predicted elastic moduli were only 2%~5% higher than experimental results. This good agreement shows that the three dimensional plain knit model as well as the input data for its impregnated fibers and matrix are appropriate for predicting the elastic modulus of the plain knit composite.

4.2. Fracture Process

4.2.1. Fracture process obtained from tensile tests

Damage development in the specimen gauge length was recorded using a video camera. Photographs of the specimen in the wale direction taken at three different stages of tensile loading are shown in Fig.5. At stage 1 (applied tensile stress = 41.5MPa approximately, Fig.4), matrix cracking at head portions of needle and sinker loops was observed (Fig.5a) with whitening. With further increase in applied stress, in the stage 2, cracks propagated through resin rich regions in the widthwise direction of the specimen, leaving the fiber bundles which were still bridging fracture planes bear most of the

Table 2. Tensile moduli obtained from FEM and experiments

Method	Elastic Modulus E , GPa	
	Wale	Course
FEM	5.9	4.6
Exp.	5.6	4.5

a) Initial cracking of the matrix resin.

b) Failure of the matrix resin at the stage 2.

c) Failure of fiber bundles at the stage 3.

Fig.5. Optical photographs showing the fracture process of the matrix and fiber bundles in the wale direction.

applied load. Then they would quickly come to fail (Fig.5b). Finally, at the stage 3, the applied stress was around 60 MPa, the failure of the fiber bundle which bridged the fracture planes occurred, thus resulted in

separation of fracture surfaces. In that case the composite was considered to fail (Fig.5c).

Unlike the wale direction, the tensile damage accumulation stages could not be identified clearly because specimens failed suddenly without prior damage indication in the course direction (Fig.6). Complete separation of fracture surfaces took place with the fracture of fiber bundles bridging the fracture planes.

The SEM photograph of the wale fracture surfaces is shown in Fig.7. The fracture surface contains both the debonded knit loops and fractured fiber bundles that failed at side limb and interlocking points of the plain knit fabric. The following SEM photograph illustrated in Fig.8 more clearly indicates debonding and fractured fiber bundles of the course specimen although the stages of damage accumulation were not caught by the video camera. Debonded knit loop fiber bundles were also observed. It is evident that the fiber bundles failed mainly at sinker loop region.

10 mm

Fig.6. Optical photograph showing the fracture process of the matrix and fiber bundles in the course direction.

4.2.2. Fracture process obtained from numerical analysis

Fracture process of the plain knit-fabric composite depends strongly on initial cracking that occurred in the matrix resin or fiber elements. Thus stress distribution of each fiber and matrix beam elements was simultaneously calculated with incremental displacement enhanced in each amount of 0.03mm. When applied strain reached 1%, initial fracture of surface resin elements at the needle loop of the wale direction and the crossover B resin elements failed.

The fractured resin elements denoted by thin dotted lines (Fig.9a) illustrate initial fracture in the wale direction. With further increase in the applied strain, the other surface elements and crossover A resin elements failed. Finally, fiber elements in the crossover parts failed when the applied strain was around 3% (Fig.9b).

This process was similar to that observed in the experiment which was described in the previous section: the cracking of matrix resin initially occurred and the frac-

Fig.7. SEM photograph of the fracture surface showing debonding and fractured fiber bundles in the wale direction.

Fig.8. SEM photograph of the fracture surface showing debonding and fractured fiber bundles in the course direction.

Fig.9. Fracture process predicted by the numerical analysis in the wale direction.

Fig.10. Fracture process predicted by the numerical analysis in the course direction.

tured plane followed an array of knit loop fiber bundles. The fracture of the fiber bundles bridging the fractured plane resulted in the ultimate fracture of the composite specimen.

The events leading to the fracture of the course specimen obtained from the numerical analysis are illustrated in Fig.10. Initially, the surface resin elements on the sinker loop region failed (Fig.10a). The initial matrix cracking also occurred in the surface resin elements where the highest stresses were concentrated. With further applied strain the number of fractured surface resin elements increased and also the fracture of resin elements at the crossover B occurred. Finally, the fiber element of the sinker loop failed (Fig.10b); the failure of the fiber element was regarded as the failure of the composite.

5. CONCLUSIONS

The three-dimensional finite element model has been proposed for predicting the tensile modulus of the glass fiber plain knit fabric reinforced epoxy composites. The reasonable agreement between the numerical and experimental results shows that the 3-D finite element model is available for predicting the elastic modulus of the plain knit fabric composite.

The sequence of events leading to the final fracture of the composite was similar for both the wale and course directions. Initially, the cracking of resin matrix occurred at the head of the needle or sinker loops, then, cracks propagated through the adjacent resin rich regions normal to the loading. Finally, fiber bundles failed and also the path of the fracture surface was not the same for the wale and course specimens. In the wale specimens, the fracture surface contains needle loops, sinker loops and the interlocking regions of the knitted structure. In fact, the fiber bundles mainly failed in the interlocking regions of the plain knit structure. In the course specimens, the fracture surface contains an array of knit loop fiber bundles, which are oriented transverse to the testing direction. The fracture of sinker loop fiber bundles resulted in the failure of the composite.

The fracture process obtained from the numerical analysis is similar to the one obtained from experiments in both the wale and course directions, i.e. surface resin elements at needle and sinker loops initially occurred and

then the other resin elements failed. Finally, the fracture of the fiber bundles led to the complete failure of the composites.

The numerical model used in this study has not been applied to the fiber/matrix interface region, as the material constants of the interface region were not available, however it is possible to incorporate additional elements into the model to represent the fiber/matrix interface region.

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