1 Introduction

Woven composite materials have long been recognized as being more competitive than unidirectional composite materials for their good stability in the mutually orthogonal warp and fill directions. This is attributed to more balanced properties in the fabric plane and enhanced impact resistance. These advantages have resulted in a growing interest in the use of woven composites for structural applications [1, 2]. Z-pinning is one of the several ways to reinforce through-the-thickness direction properties. The process of producing z-pinned composites is more productive and affordable than for other reinforcement methods, due to its simplicity, while, the disadvantages of inserting z-pins in composite materials decrease for in-plane properties [3]. There are many studies about the predictions of composite properties, but few researches are currently being carried out on the woven composites materials into which some other materials are inserted for the reinforcement. Lin et al. used unit-cell model based on classical laminate theory. This approach transfers the stiffness of the z-pin to the laminate plane and adds the stiffness of the z-pin to the in-plane laminate stiffness [4]. Tanov et al. suggested micro mechanical models using the method of cells and the four-cell method, respectively. A cell is divided into many sub-cells and an averaging method is then applied that assumes a uniform stress distribution for each sub-cell in order to obtain the effective stress-strain relationships of the sub-cell [5].

Despite the range of previous studies, research regarding numerical prediction for woven z-pinned composites has never been performed. In the present study, the mechanical properties of woven z-pinned composites containing complicated geometric information are analytically predicted. A unit-cell model is developed in order to predict mechanical properties as a function of graded waviness for laminates that are created by z-pinning or weaving and include resin rich zones. Mechanical properties are predicted for z-pin diameters, lengths of the resin rich zone, and warp and fill thicknesses. Theoretical predictions are experimentally validated for various z-pin densities via tensile and shear tests.

2 Geometric Characterization of Woven Z-pinned Composite

In this study, a constitutive model is developed for the prediction of mechanical properties of woven z-pinned composites. After the insertion of z-pins in the through-the-thickness direction within composite materials, z-pinned composites exhibit pockets called resin rich zones surrounding the z-pins.

Fig.1. Various shapes of the resin rich zone in accordance with the z-pin's insertion location

When the z-pin is inserted in the middle of the yarn as both warp and fill, the resin rich zone forms the shape of a cat’s eye, as shown in Fig.1(a). However, some woven z-pinned composites have unusual resin rich zones, as shown in Fig. 1(b), which illustrates a right-sided resin rich zone, and Fig. 1(c), which illustrates a left-sided resin rich zone. In experiments to estimate fabricated woven z-pinned composite specimens, regular shaped resin rich zones appear more often than unusual shaped resin rich zones. Therefore, the insertion of the z-pin in the center of
the warp and fill, due to the limitation of considering all variations of the resin rich zone, is hypothesized and then it is assumed that the insertion of z-pin is in the z-direction only.

2.1 Unit-cell

Woven z-pinned composites are constructed by interlacing warp yarns lengthwise and fill yarns crosswise at right angles and by inserting z-pins in the center of the warp and fill, as shown in Fig.2 (a). It is defined by simplifying the repeated part of the woven z-pinned composite, as shown in Fig.2 (b). Woven z-pinned composite has repeated parts at one distance of the z-pin, as depicted by the blue square shown in Fig.2 (b). However, a unit-cell is defined as a red square, as shown in Fig.2 (b), in order to reduce the numerically predicted time because the blue square region is up and down and left and right in relation to the symmetric structure of the z-pin.

![Fig.2. Cross-section of woven z-pinned composites](image)

![Fig.2. Woven z-pinned composite architecture](image)

2.2 Sub-cell

The unit-cell can be finely divided in the out-of-plane direction and defined by combining various property models of the block. Sub-cells are defined according to fiber waviness in the out-of-plane direction. Therefore, a unit-cell has 10 sub-cells and, based on the graded fiber characteristic, can be expressed as shown in Fig.3. 10 sub-cells are defined according to fiber waviness. Sub-cell 1 consists of a z-pin, as shown in Fig. 3(a), and sub-cell 2 consists of resin due to the resin rich zone in warp and fill, as shown in Fig.3 (b). Sub-cells 3, 4, 9, 10 all consist of warp, fill, and resin. Sub-cells 5, 6, 7, 8 consist of either warp and resin or fill and resin. These sub-cells are divided according to fiber waviness caused by the z-pin and graded warp and fill. In Fig.3, the fiber waviness is affected by the diameter of the z-pin, the aspect ratio of the resin rich zone, and yarn thickness. The z-pin density is an important factor governing the mechanical properties of woven z-pinned composite. Therefore, when modeling unit-cell geometry, the most important parameters affecting the properties of woven z-pinned composites are z-pin diameter, stitching density of the z-pin, the resin rich zone shape, and the thickness of warp and fill.

![Fig.3. Subdivisions in accordance with characteristics of graded waviness of laminate for unit-cell](image)

2.3 Yarn Architecture

The properties of woven z-pinned composites depend upon the geometric pattern of the graded fiber and the resin rich zone. The mechanical properties of general composite materials are dramatically changed due to fiber orientation changes because the fiber orientation is affected by the previously defined parameters, which are as follows: the z-pin’s diameter, the resin rich zone’s shape, and the thickness of warp and fill. In order to predict the mechanical properties of the
woven z-pinned composites, a geometric model is developed for the woven z-pinned composites. Therefore, the equations are defined in terms of the parameters caused by the fiber waviness; the z-pin’s diameter, the resin rich zone’s shape, and the thickness of warp and fill.

3 Elastic Properties of Woven Z-pinned Composites

3.1 Coordinate System

The mechanical properties of woven z-pinned composites can be predicted based on the laminate, z-pin, and resin properties. The unit-cell architectures that result are from the geometric model. Since the fiber’s principal direction does not coincide with the coordinate direction of the unit-cell, a method is needed for transforming the stress-strain relations from one coordinate system to another.

3.2 Volume Averaging Method

Since the effective compliance for the warp and fill subdivisions, created based on the characteristics of graded laminate waviness, has been obtained, the deformation properties for woven z-pinned composites can be predicted via the volume averaging method of those yarns based on the correct assumption of iso-stress or iso-strain.

3.3 Z-Pin Density

It is impractical to insert z-pin for all warp and fill in real life-woven z-pinned composites. In order to validate the predicted mechanical properties for woven z-pinned composites, the predicted equations, according to the previous explanations, need to be modified according to the z-pin densities.

Mechanical properties of woven z-pinned composites, as a density of z-pin, are obtained using series-model and parallel model in the section with z-pin and without z-pin. The value \( n \) representing the degree of densities is obtained from the division of distance for previously defined unit-cells by distance between z-pins. That means \( n = 1 \) when the z-pin is inserted into each warp and fill. However, the less the z-pin is inserted, the less the amount of \( n \). Therefore, \( n \) is zero without z-pin on the specimen.

\[
(n \text{ (z-pin density)}) = \frac{\text{Distance of modified unit-cell}}{\text{Distance of z-pins}} \quad (1)
\]

4 Experimental Procedures

The specimens investigated in this study were made from Glass/epoxy and z-pins were made of carbon tows. The material properties for constituents of the specimen are shown in Table 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>( E_1 ) (GPa)</th>
<th>( E_2 ) (GPa)</th>
<th>( E_3 ) (GPa)</th>
<th>( G_{12} ) (GPa)</th>
<th>( G_{23} ) (GPa)</th>
<th>( G_{13} ) (GPa)</th>
<th>( v_{12} )</th>
<th>( v_{23} )</th>
<th>( v_{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass epoxy laminate</td>
<td>41</td>
<td>10.4</td>
<td>10.4</td>
<td>4.3</td>
<td>3.5</td>
<td>4.3</td>
<td>0.28</td>
<td>0.50</td>
<td>0.28</td>
</tr>
<tr>
<td>Carbon tow Z-pin</td>
<td>144</td>
<td>7.31</td>
<td>7.31</td>
<td>4.45</td>
<td>2.65</td>
<td>4.45</td>
<td>0.25</td>
<td>0.39</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Three different specimen types are used as follows: without the z-pins, with the distance of 5mm between the z-pins, and distance of 3.5 mm between the z-pins. Each of the three is stacked with ten layers of woven z-pinned composite with each yarn measuring 0.375 mm in thickness. A z-pin with a radius of 0.48 mm was inserted into many specimen types. All specimens are configured with warp and fill with each measuring a width of 0.67 mm, a length of 0.49 mm in resin rich zone and a height of 0.3 mm in graded fiber, respectively. Fig.4 shows pictures of three composite specimens with various z-pin densities.

Tensile tests are carried out according to ASTM D3039 and the shear tests according to Iosipescu tests. The tests are conducted in a MTS 810.23 servo-hydraulic testing system. The specimens of woven z-pinned composites are examined with commercially available strain gages (EA and LZ gages from Measurements Group, Inc.) for measuring longitudinal and transverse strains.

Fig.4. Three woven z-pin composite specimens (a) without z-pin, (b) \( d=5\text{mm} \), (c) \( d=3.5\text{mm} \)

5 Results and Discussion

In order to verify the predicted mechanical properties of z-pinned composite, they are compared to those of the examined mechanical properties. The mechanical properties were obtained from the stress-strain curves from tensile and shear tests. Fig.5 compares the
predictions and experiments for the in-plane mechanical properties as a function of z-pin densities for the woven z-pinched composites. A positive correlation between the numerical and experimental results is observed within in-plane properties having less than a 2.8% error average. The shear modulus for specimens with the highest density of more than \( n = 0.4 \), results in the highest error of 5.6%, due to the lack of consistencies in incident angle and geometry of the resin rich zone, as the density of z-pin increased.

Fig.5. Predicted and experimental results as a function of z-pin densities for woven z-pinned composite (a) longitudinal moduli, (b) in-plane shear moduli, (c) Poisson’s ratio

Fig.6 shows the change rates for the mechanical properties of the woven z-pinned composites as a function of z-pin diameter. In-plane properties decrease and out-of-plane properties increase as the diameter of z-pin increases from 0 mm to 0.5 mm. The increase amount for the out-of plain properties is twice as much as the amount of decrease for the in-plane properties. In-plane elastic modulus decreases by 8% and the out-of-plane elastic modulus increases by 18% as the diameter of the z-pin increases from 0 to 0.24mm. For the case of the shear modulus, the mechanical properties of both in-plane and out-of-plane decrease when the diameter of the z-pin increases. The ratio of decrease is larger by approximately 5% on the in-plane when the z-pin’s diameter changes from 0mm to 0.24mm. Poisson’s ratios are not affected by the changes of the z-pin’s diameter.

Fig.6. Mechanical properties for z-pinned composites as a function of z-pin diameter;
(a) Normalized in-plane elastic modulus \( (E_x) \),
(b) Normalized out-of-plane elastic modulus \( (E_z) \),
(c) Normalized in-plane shear modulus \( (G_{xy}) \),
(d) Normalized out-of-plane shear modulus \( (G_{yz}) \),
(e) Normalized in-plane Poisson’s ratio \( (\nu_{xy}) \),
(f) Normalized out-of-plane Poisson’s ratio \( (\nu_{yz}) \)

Fig.7 shows the change rates of elastic modulus, shear modulus, and Poisson’s ratio on the in-plane and out-of-plane as a function of the resin rich zone’s distance. The elastic modulus slightly increases as the long distance of the resin rich zone increases and this is due to the conflict effect. As the increase of long distance of the resin rich zone creates a decrease in laminate waviness, this phenomenon causes the increase of in-plane properties. However, as the resin is replaced by the laminate, the increase in the resin rich zone amount causes a decrease in the mechanical properties. The amount of decrease for the out-of-plane mechanical properties is larger than the amount of increase for the in-plane due to the decrease in the out-of-plane because of the resin’s replacement. There is no change of shear modulus and Poisson’s ratio as a distance of resin rich zone.
Fig. 7. Mechanical properties for z-pinned composites as a function of the resin rich zone length;
(a) Normalized in-plane elastic modulus ($E_x$),
(b) Normalized out-of-plane elastic modulus ($E_z$),
(c) Normalized in-plane shear modulus ($G_{xy}$),
(d) Normalized out-of-plane shear modulus ($G_{yz}$),
(e) Normalized in-plane Poisson’s ratio ($v_{xy}$),
(f) Normalized out-of-plane Poisson’s ratio ($v_{yz}$).

Fig. 8. Mechanical properties for z-pinned composites as a function of the thickness variation of yarn. As the thickness of yarn increases, the in-plane elastic modulus decreases and the out-of-plane elastic modulus increases due to the increase of z-direction waviness. Showing similarity, both shear moduli decrease only slightly and there is no significant difference in Poisson’s ratio.

In conclusion, in order to obtain an increase in out-of-plane mechanical properties, the increase of the z-pin diameter is the most important change when compared to the others. Also, the decrease in the long distance of the resin rich zone prevents the decrease in the out-of-plane mechanical properties. Therefore, the technology used to reduce the size of the resin rich zone by inserting z-pin is the most effective method for increasing out-of-plane mechanical properties for woven z-pinned composite.

6 Conclusions
This paper proposes a model for predicting both the in-plane and out-of-plane mechanical properties by defining the sub-cell of the woven z-pinned composites. Unlike previous studies, this model considers both the resin rich zone for insertion of z-pin and fiber waviness. The two values compared both their experimental and numerical data and were found to be in good agreement and, therefore, the model has been verified.

The increase amount for the out-of-plane properties is twice as much as the amount of decrease for the in-plane properties. Through these results, the increase in the out-of-plane properties is verified. Also, this paper shows the change in mechanical properties for both in-plane and out-of-plane because the proposed model of this paper is considering all geometric parameters. The geometric parameters considered within this paper are as follows: the diameter of the
z-pin, the long distance of resin rich zone, and the thickness of yarn. By changing the mechanical properties of these variables, the most sensitive parameters are selected. The most sensitive parameter of this study is the diameter of z-pin, the others parameters are less sensitive to the mechanical properties of the woven z-pinned composite than the diameter of z-pin. As a result, this proposed model is very useful for analyzing structures using woven z-pinned composite.

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