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Research Article

Experiment and Simulation Investigation on the Tensile Behavior of Composite Laminate with Stitching Reinforcement

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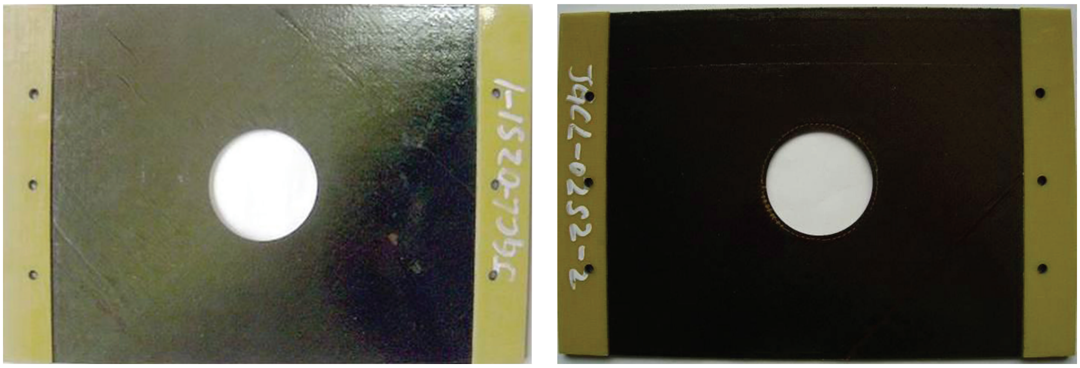
The experiments and finite element simulations of composite laminate with stitching are carried out. Firstly, the monotonous tensile experiments with and without stitching are conducted to investigate the influence of stitch reinforcement on the composite laminate. Secondly, the finite element method (FEM) is employed to simulate the tensile process of specimens, and the link element is introduced to simulate the stitching. The experiment results shows that the stitching has little influence on the damage load under monotonous tensile load, while there is a significant influence on the changing of strain. The FEM results are consistent with the experiment results, which means that the link element can be used to study the stitching of the composite laminate. The simulation results also show that the distributions of strain are changed obviously due to the existence of the stitching. Research results have a significant role on the design of the composite structures with and without stitching.

1. Introduction

Carbon fiber-reinforced advanced composites are widely used in aircraft, airspace and other fields due to its high strength to weight ratio, stiffness to weight ratios and the potential to increase fatigue, corrosion resistance, and quake-proof damping. In order to satisfy the requirements of assembly, the composites plane usually open some holes although there is serious stress concentration. And the stripping, stress will be raised around the hole as the anisotropic property of the composite, which decreases the strength of the composite structure [1].

The delamination damage usually occurs at the lower stress level due to the two dimension (2D) laminate property, which leads to bad interlaminar mechanics. There are many kinds of methods to improve the out-of-plane mechanics, in which stitching is an idea method, as it is simply high-performance-to-price ratio. However, the stitch reduces the mechanics performance of composite due to the existence of the initial inner-plane damage. In the previous works, Deng et al. found that the density of the initial inner-plane damage induced by the stitching process is determinate by the stitch density and the diameter of the thread [2]. The inner-plane tensile-strength of the composite structures is reducing with the increment of the stitch density or the diameter of the thread. Aymerich et al. studied the influence of stitching on the fracture behavior of cocured single-lap joints under fatigue loading by means of experimental and numerical analysis. And the results show that stitching could not improve the static strength of joints, while it significantly extends both the crack initiation and crack propagation phases and improve the fatigue damage tolerance [3]. Lascoup et al. found that stitching between the core and the skins can increase mechanics properties in the thickness direction of sandwich structures although the mass is added [4]. Dransfield et al. studied the toughness of the composite laminates with stitching, which shows that the stitching can improve the delamination toughness of the composite laminates and the damage tolerance of the boned joints [5, 6]. Wood conducted tabbed stitched DCB experiments using



(a) Unstitching (b) Single-line stitching reinforced

Figure 1: The specimens with and without stitching.

three types of stitch distribution with the same stitch density [7]. It is found that stitch distributions play an important role in determining the steady state strain energy release rate. Hess et al. developed a finite element unit-cell model to estimate the elastic constants of structurally stitching non-crimp fabric laminates taking into consideration the yarn diameter, the stitching pattern and direction, and the load direction [8].

In this paper, the tensile experiments of composite plane without stitching and single-line stitching reinforce were carried out to study the influence of stitching on the mechanical behavior of composite laminate. And the finite element method (FEM) was employed to simulate the tensile process of specimens. Furthermore, the damage mechanism of composite plane with stitching reinforce is discussed.

2. Experimental Procedure

Two kinds of composite specimens with single hole are designed to carry out tensile experiments. The first specimen is unstitched, while the second is stitched around hole. The two kinds of specimens are shown in Figure 1. For the composite laminates, the carbon fiber is T300, and the matrix is 9512 Epoxy. The detailed stacking sequences is $[45/0_2/-45/90/0_2/-45/0]$ s. The thickness of each layer is 0.12 mm, and the deviation standard is 8% after cocured process. The volume ratio of the fiber is $62 \pm 2\%$. In order to mount the specimens into the gripping system of the testing apparatus and strengthen the ends of the specimen, 200 mm × 30 mm glass cloth end tabs are applied to the specimen by adhesive bonding. The circum and the surface of the specimens with holes are coated with H01-101H varnish. The stitching mode is modified lock stitch. The specimens are divided into two groups, which can be seen in Table 1.

Table 1: Groups of the specimens.

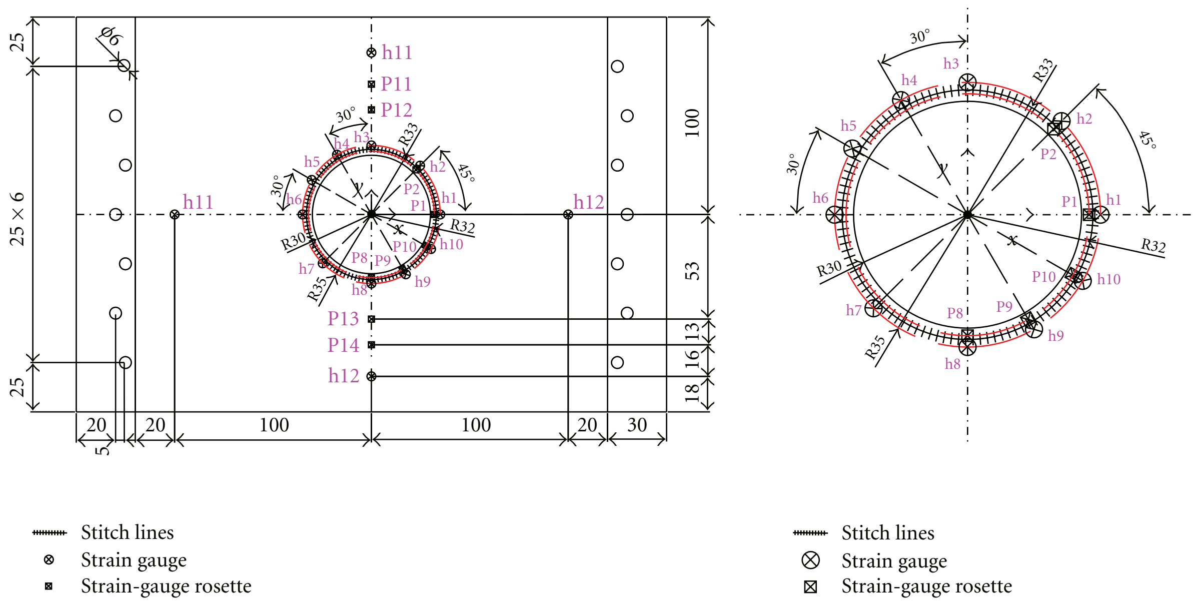
Category	Serial number	Range between the stitch line to the hole edge (mm)	Thread space (mm)	Numbers
Unstitching	02s1			3
Single-line stitching	02s2	3	3	5

2.1. Experiment Method. The experiment is carried out by the INSTRON100T machine. The locations of strain gauges of single-line stitching specimen are shown in Figure 2. The signals of each strain gauges and pressure transducer are measured simultaneously by an A/D converter. The tensile loading was added 2 KN per step in the initial stage; the incrimination is changed to 1 KN per step at the secondary stage until the appearance of the damage. The whole tensile configuration is shown in Figure 3, and the damaged specimen is shown in Figure 4.

2.2. Experiment Results. The maximum load of specimen without stitching is 32.02 KN, and the maximum load of specimen with stitching is 32.19 KN. It can be concluded that stitching has little influence on the damage load under monotonous tensile load condition. The main damage pattern is matrix compression failure and fiber tension failure although interlaminar damage occurs at local zones around the hole. So, the effect of stitching is not obvious. New stress concentration induced by stitching make the stress distribution around the hole edge much complex, which bring the disadvantage to the strength of specimen.

Further, the strains located at 0°, 45°, and 90° around the circle with radius 32 mm are selected to study the influence of stitching on the strain distributions. In (1), ε_Φ ($\Phi = 0^\circ, 45^\circ, 90^\circ$) represents the circumferential strain (ε_θ). And the sketch map is shown in Figure 5, which describes the location of the points to be compared

$$\begin{aligned} \varepsilon_0 &= \frac{1}{2}(\varepsilon_A + \varepsilon_{A1}), \\ \varepsilon_{45} &= \frac{1}{4}(\varepsilon_B + \varepsilon_{B1} + \varepsilon_{B2} + \varepsilon_{B3}), \\ \varepsilon_{90} &= \frac{1}{2}(\varepsilon_C + \varepsilon_{C1}). \end{aligned} \tag{1}$$



(a) The whole body view (b) The amplification around the hole

Figure 2: Location of strain gauges attached on the single-line stitching panel (mm).

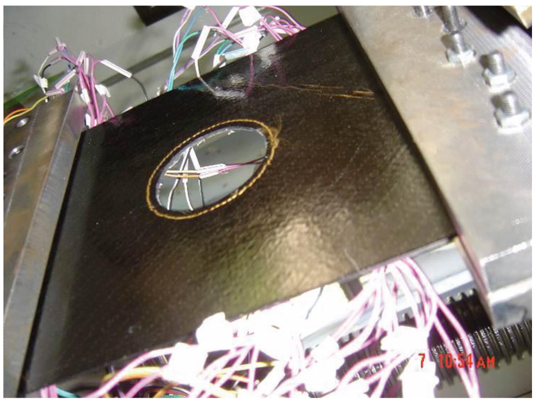


Figure 3: Experimental configuration.

Figure 4: The damaged specimen.

The strain evolution of different specimens is shown in Figure 6. It can be seen from Figure 6 that there is obvious difference between stitching specimen and unstitching specimen. The new stress concentration induced by stitching thread is significantly represented at the max tension stress zone (around 0° locations) and the max compression zone (around 90° locations).

3. FEM Analysis

The key issue of FEM is to find a suitable element to model the stitching line. This element should have the property of general spar element (tension only) and take account the influence of the element diametric. In previous works, Aymerich et al. studied the composite static tensile strength under static and fatigue load conditions through the link element given by link element model [3]. Stickler et al.

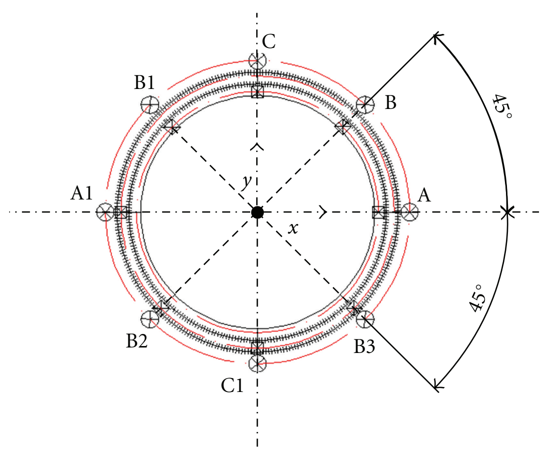
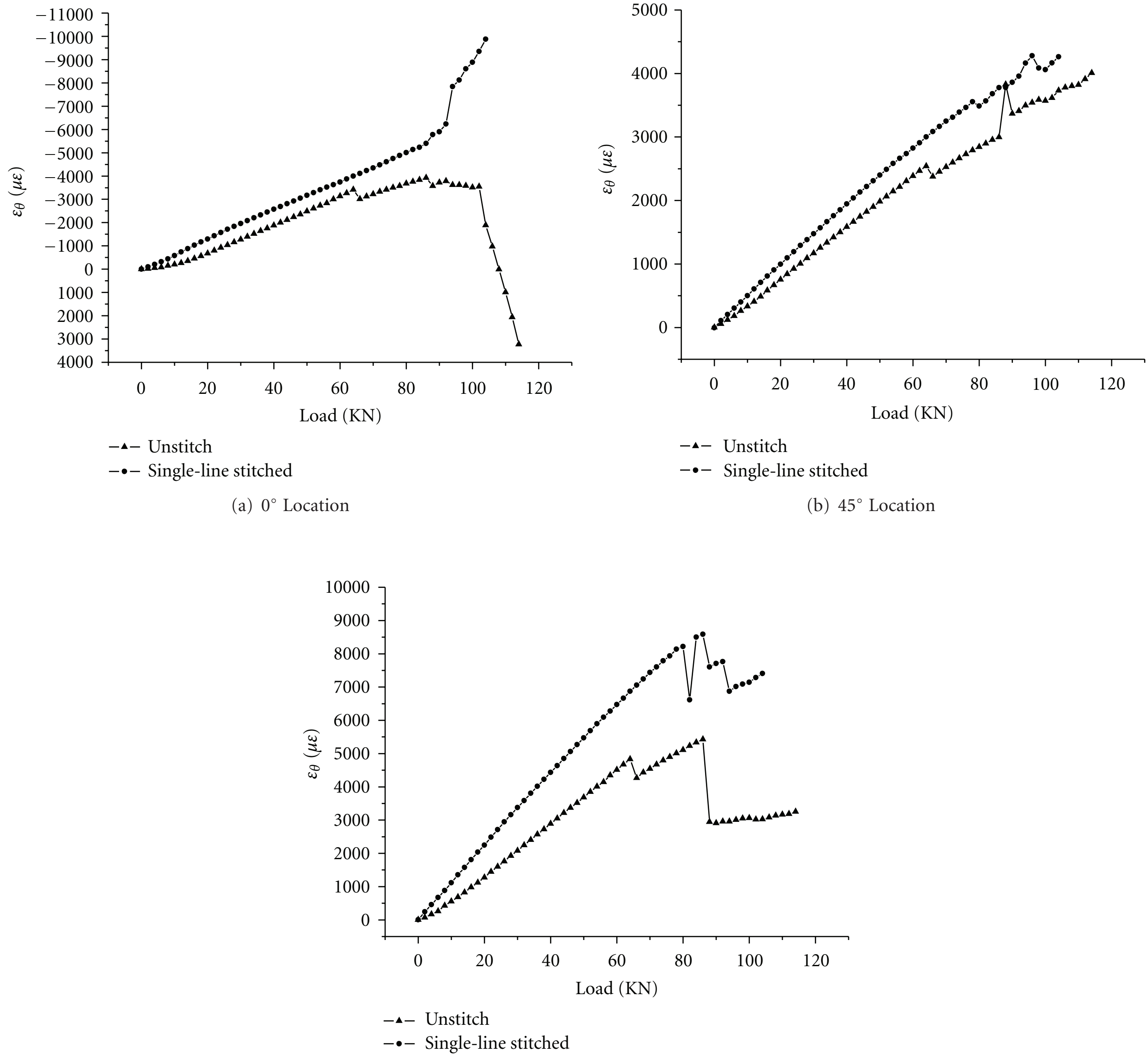


Figure 5: Location of the points to be compared.



(a) 0° Location

(b) 45° Location

(c) 90° Location

Figure 6: The strain evolution of different specimens.

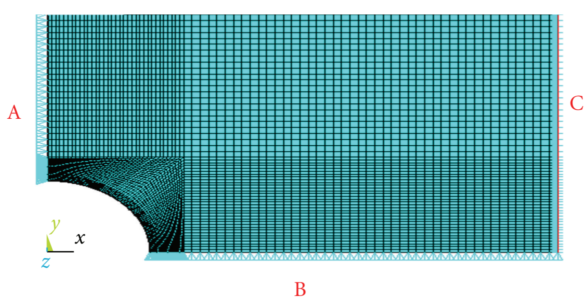
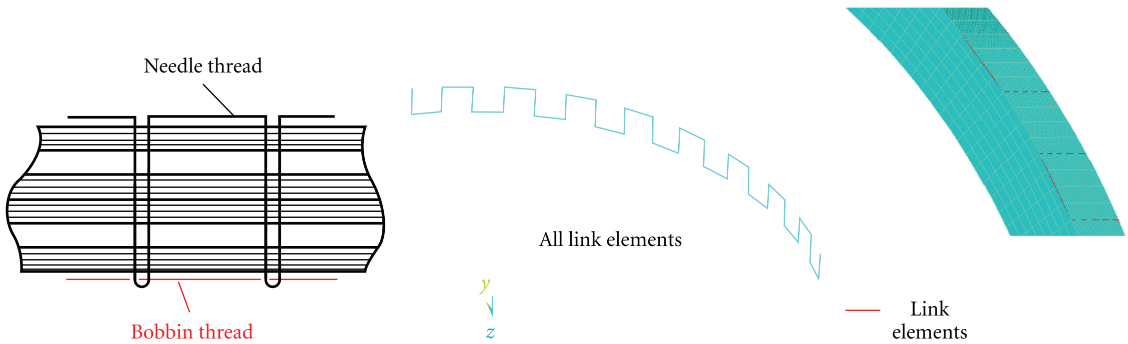


Figure 7: Finite element model.



(a) Modified lock stitching (b) Whole view of the stitching line (c) The local view of the stitch line

Figure 8: The link elements.

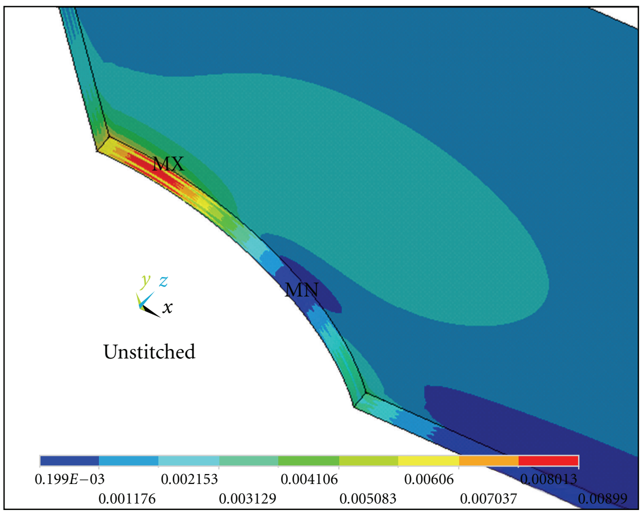


Figure 9: Mises strain distribution of the unstitching model.

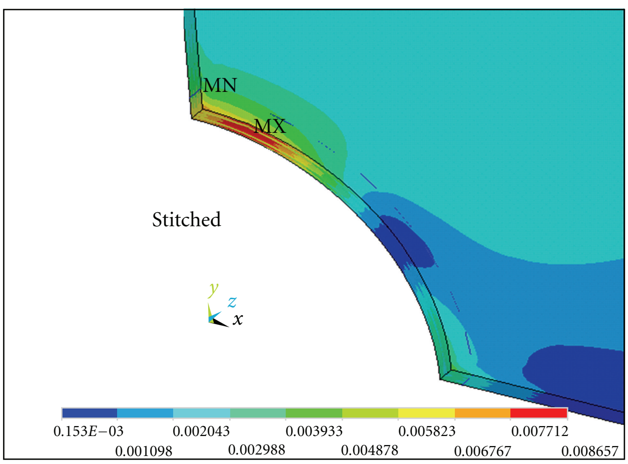


Figure 10: Mises strain distribution of the single-line stitching model.

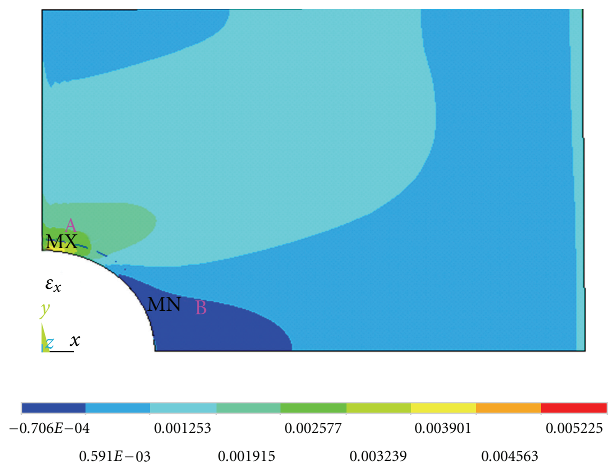
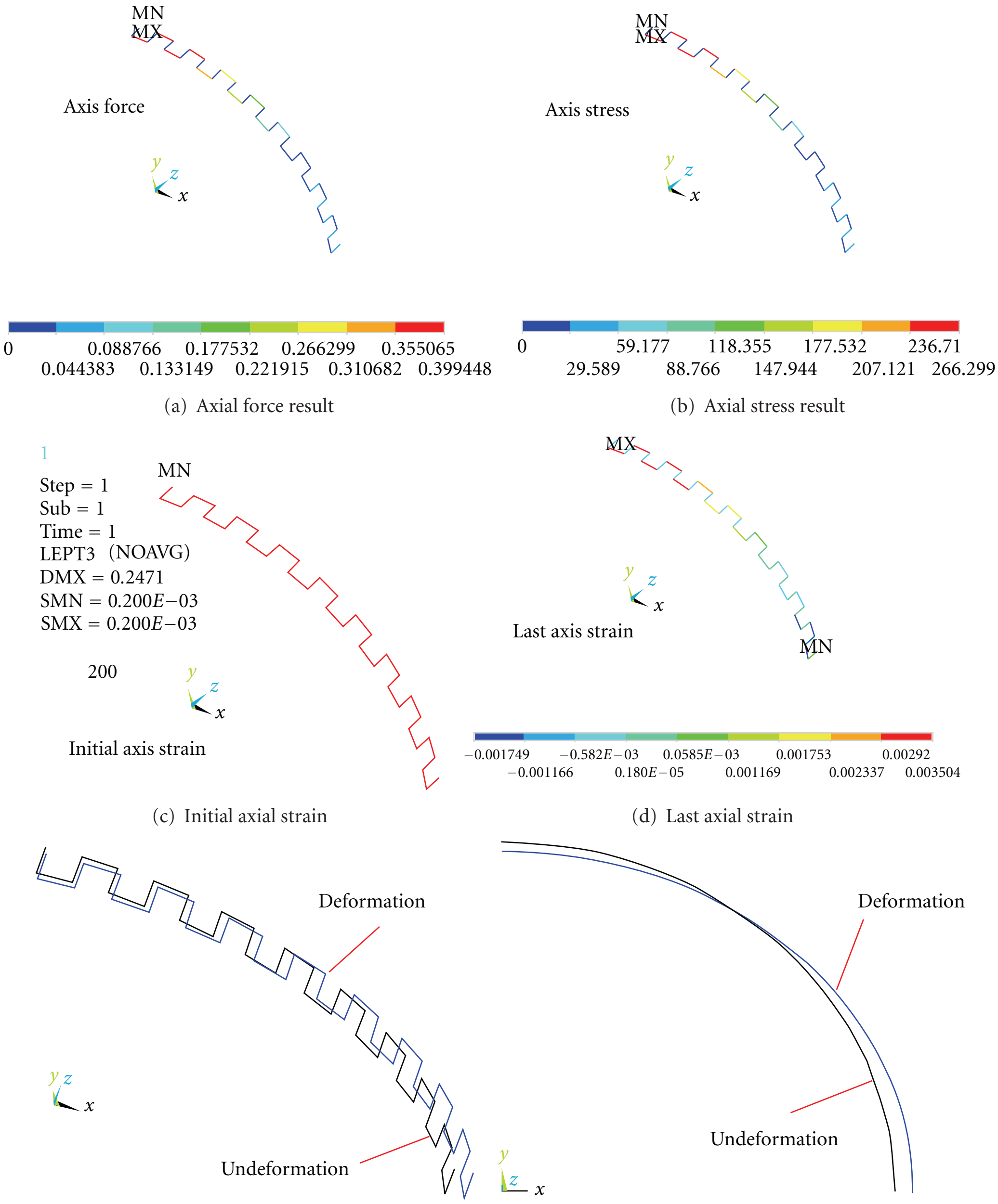


Figure 11: ε_x distribution of the single-line stitching model.

utilized the link element model to study the bending strength of transversely stitching T-joints [6]. Aymerich et al. studied the effect of stitching on the fracture response of single-lap composite joints by means of link element model. All



(a) Axial force result (b) Axial stress result

(c) Initial axial strain (d) Last axial strain

(e) Deformation of the stitch line (f) Deformation in XOY plane of the stitch line

Figure 12: Results of the stitching line.

these work show that the link element can meet the needs of FEM simulation. And this the link element is introduced to simulate the stitching line.

To simplify calculation, the composite plane with cut-out is modeled only 1/4 due to the symmetry. The elastic constants of composite laminate are as follows:

(i) $E_x = 142$ GPa, $E_y = E_z = 9.93$ GPa,

(ii) $\mu_{xy} = 0.3$, $\mu_{yz} = \mu_{zx} = 0.28$,

(iii) $G_{xy} = 5.53$ GPa, $G_{yz} = G_{zx} = 3.56$ GPa,

(iv) $E_{\text{Kevlar}} = 76$ GPa, Aera = 0.0015 mm^2.

The elastic characteristic of the Kevlar thread is come from [9]. The initial stain of it is 0.02%.

The finite element model of specimen is show in Figure 7, which is build by Ansys commercial software. The symmetry boundary condition is applied on the surface A and B. The uniform load of negative pressure is imposed on surface C, and null z-displacements are imposed on the mid line. During the calculation, the link element is used to modeling the modified lock stitch [9], which is shown in Figure 8.

3.1. FEM Results. The strain distributions of the whole model without stitching and single-line stitching are shown

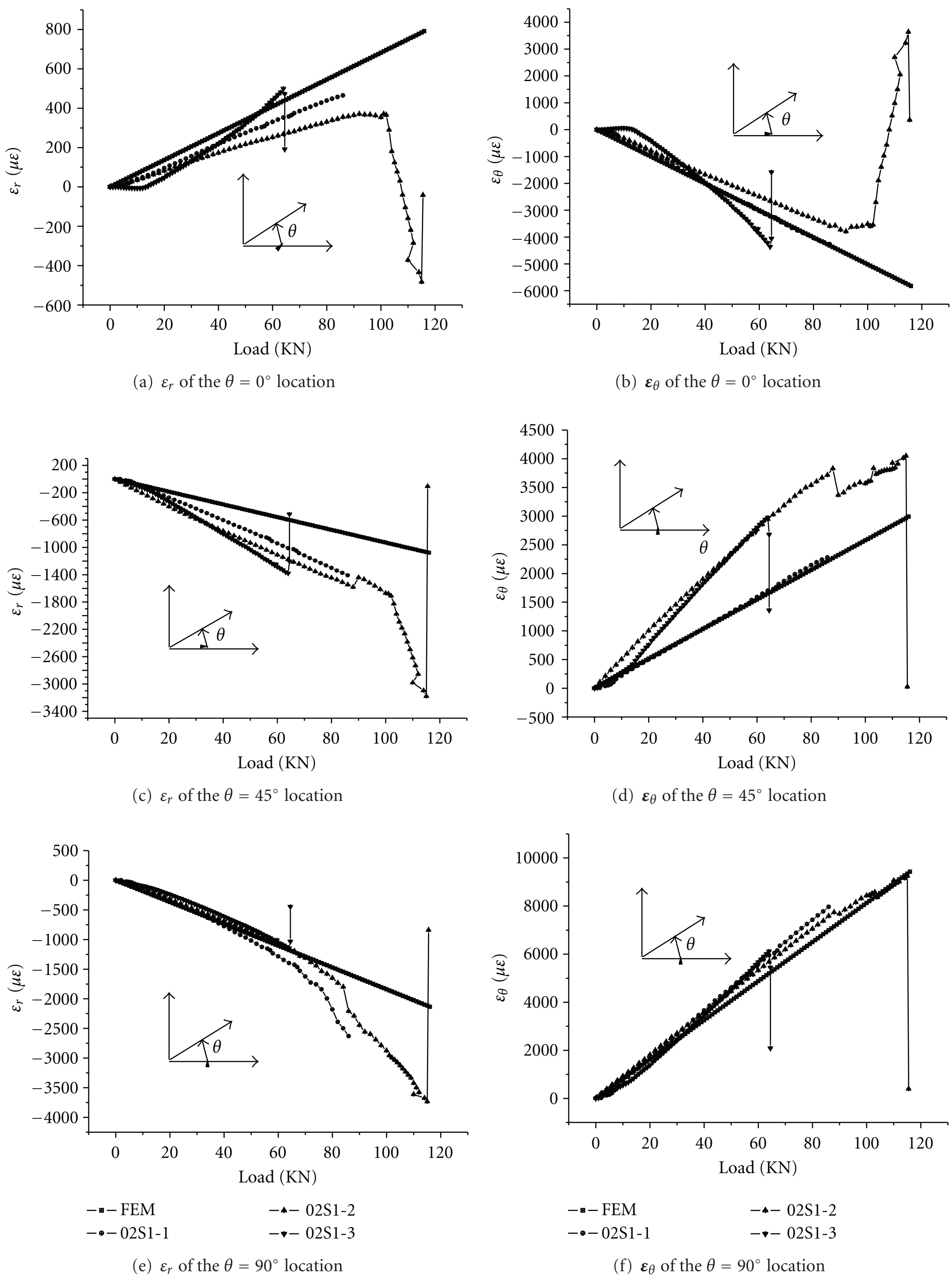
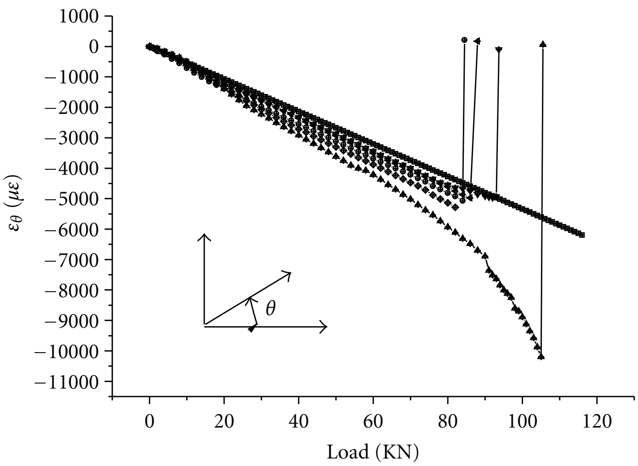


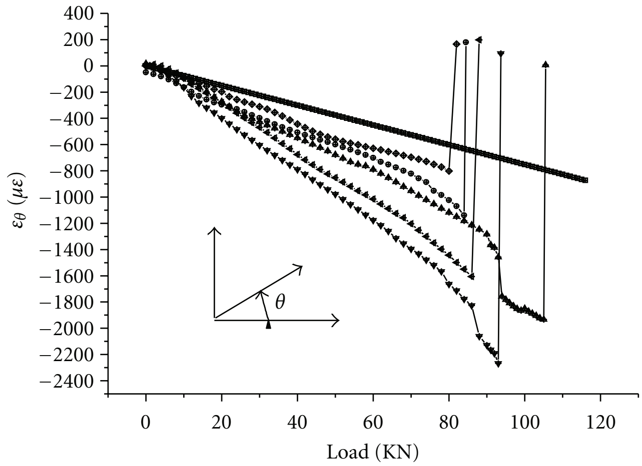
FIGURE 13: Strain of unstitching along the circle with $r = 32.5$.

as Figures 9 and 10. It can be seen from Figures 9 and 10 that the distributions of strain are changed obviously due to the existence of the stitching.

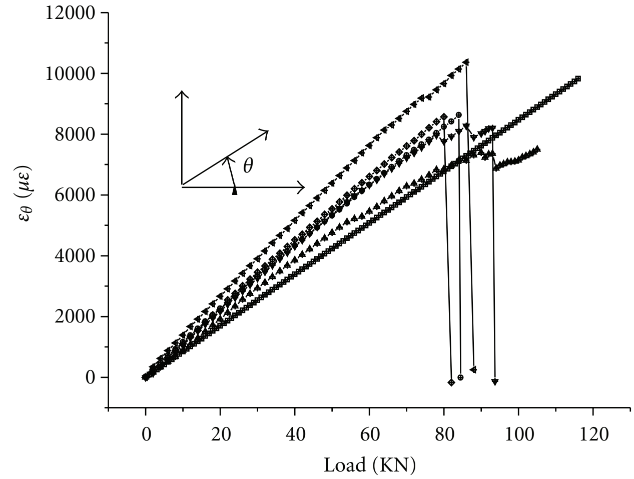
Figure 11 shows the ε_x distribution of the stitching model. In Figure 11, zone A is the tensile stress zone, and zone B is the compress stress zone. The distinction of the deformation around zone A between zone B is that zone A is shrinkage in the thickness direction, while zone B is expansion. The simulation results of the stitching line are shown in the Figure 12. It can be seen from the Figure 12 that



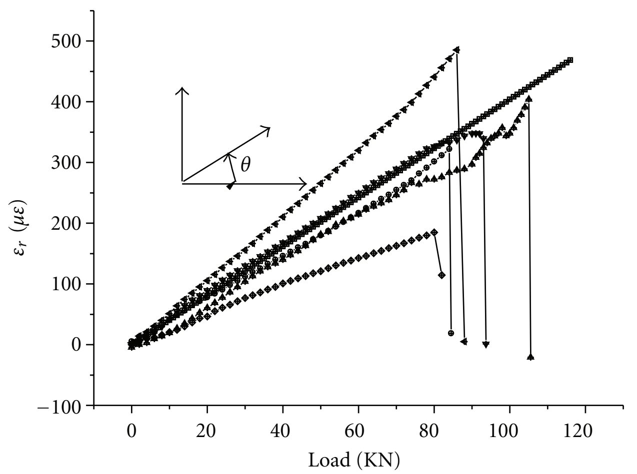
(a) $\boldsymbol{\varepsilon}_\theta$ of the $r = 32$ mm, $\theta = 0°$ location



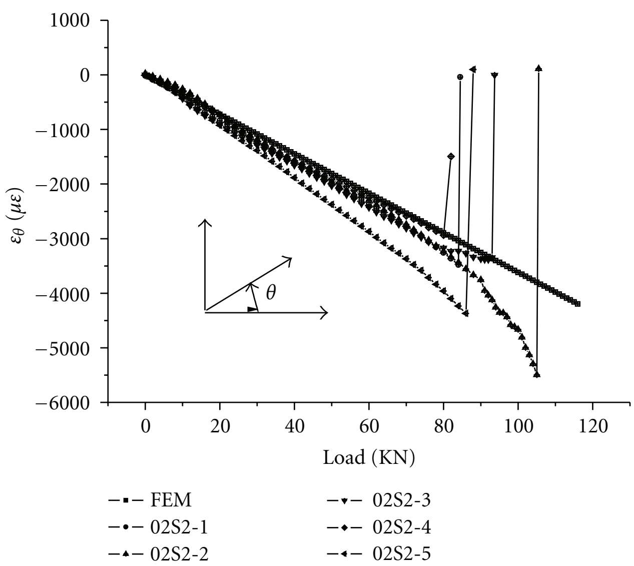
(b) $\boldsymbol{\varepsilon}_\theta$ of the $r = 32$ mm, $\theta = 30°$ location



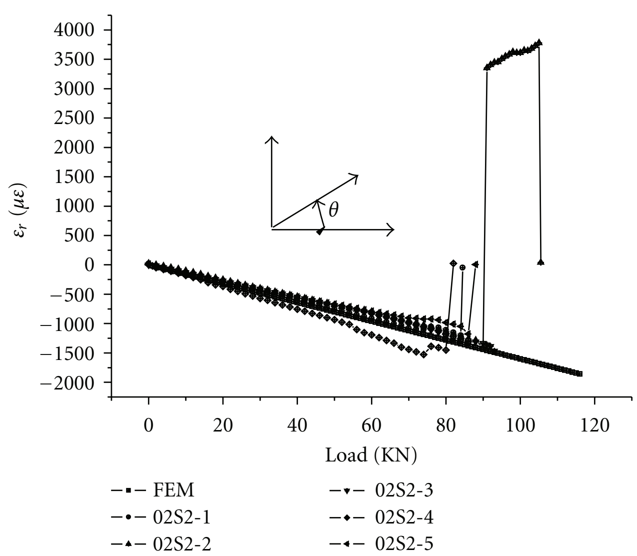
(c) $\boldsymbol{\varepsilon}_\theta$ of the $r = 32$ mm, $\theta = 90°$ location



(d) ε_r of the $r = 35$ mm, $\theta = 0°$ location

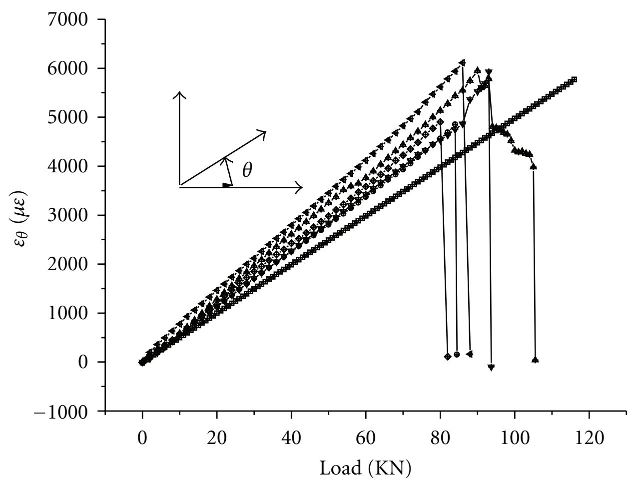


(e) $\boldsymbol{\varepsilon}_\theta$ of the $r = 35$ mm, $\theta = 0°$ location

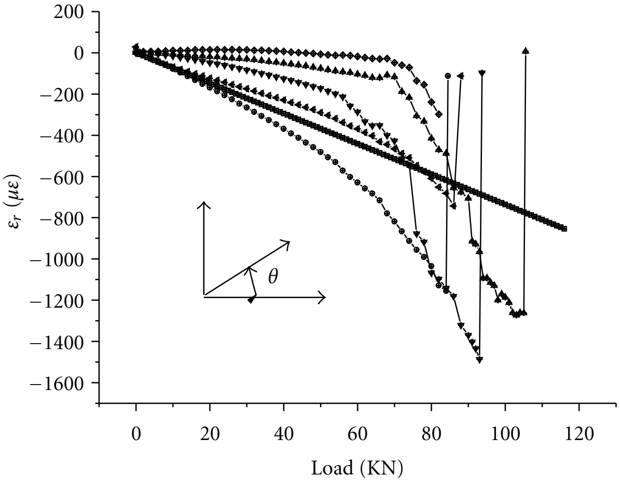


(f) ε_r of the $r = 35$ mm, $\theta = 60°$ location

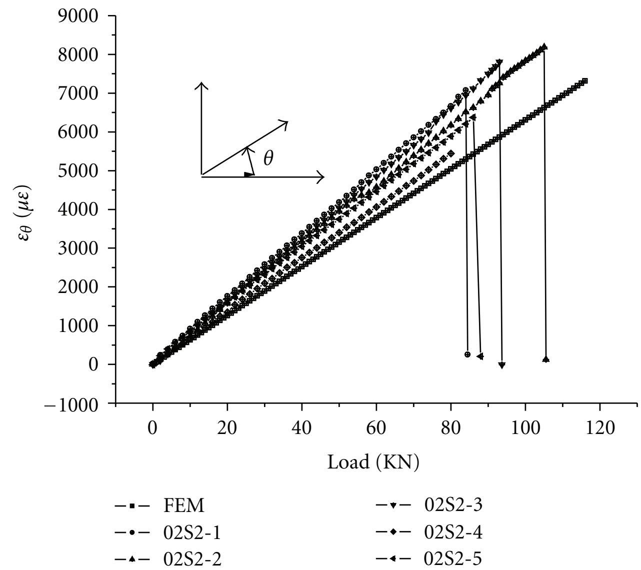
Figure 14: Continued.



(g) ε_θ of the $r = 35$ mm, $\theta = 60°$ location



(h) ε_r of the $r = 35$ mm, $\theta = 90°$ location



(i) ε_θ of the $r = 35$ mm, $\theta = 90°$ location

Figure 14: Strain of single-line stitching.

axial force, axial stress, and axial strain of the link element are increased with the decrement of y coordinate in the ply direction.

3.2. Test and Verify. The simulation results of unstitching plate are compared with the experiment results as shown in Figure 13. It can be concluded that the FEM results about the radial strain (ε_r) and the circumferential strain (ε_θ) at the two points with $r = 32.5$ mm, $\theta = 0°$, $90°$ are correspondence with the test results. The location of $\theta = 0°$ is the dangerous zone in the plate, which need much more study. Some deviation is exist at the point $\theta = 45°$, which may be caused by the deviation of strain gauges direction. All these results about load strain are linear, which prove that the linear elastic model is reasonable.

The simulation results of single-line stitching are compared with experiment results as shown in Figure 14. The FEM results on the radial strain (ε_r) and the circumferential strain (ε_θ) at all points are correspondent with the test results. It can be concluded that the method using the link element can be used to study the stitching threads.

4. Conclusions

From the results of both experimental and simulation analysis, the comprehensive conclusions of the paper are as follows.

(1) The experiments with and without stitching show that stitching could not improve the strength of composite laminate significantly under the monotonous tensile load condition.

(2) The link element can be used to investigate the stitching of composite plate. And the experiment results prove that the simulation introduced in this work is reasonable.

(3) The experiment results and simulation results shows that there is obvious effect of the stitching line on the strain of the composite plate. The distributions of strain are changed obviously due to the existence of the stitching.

Acknowledgment

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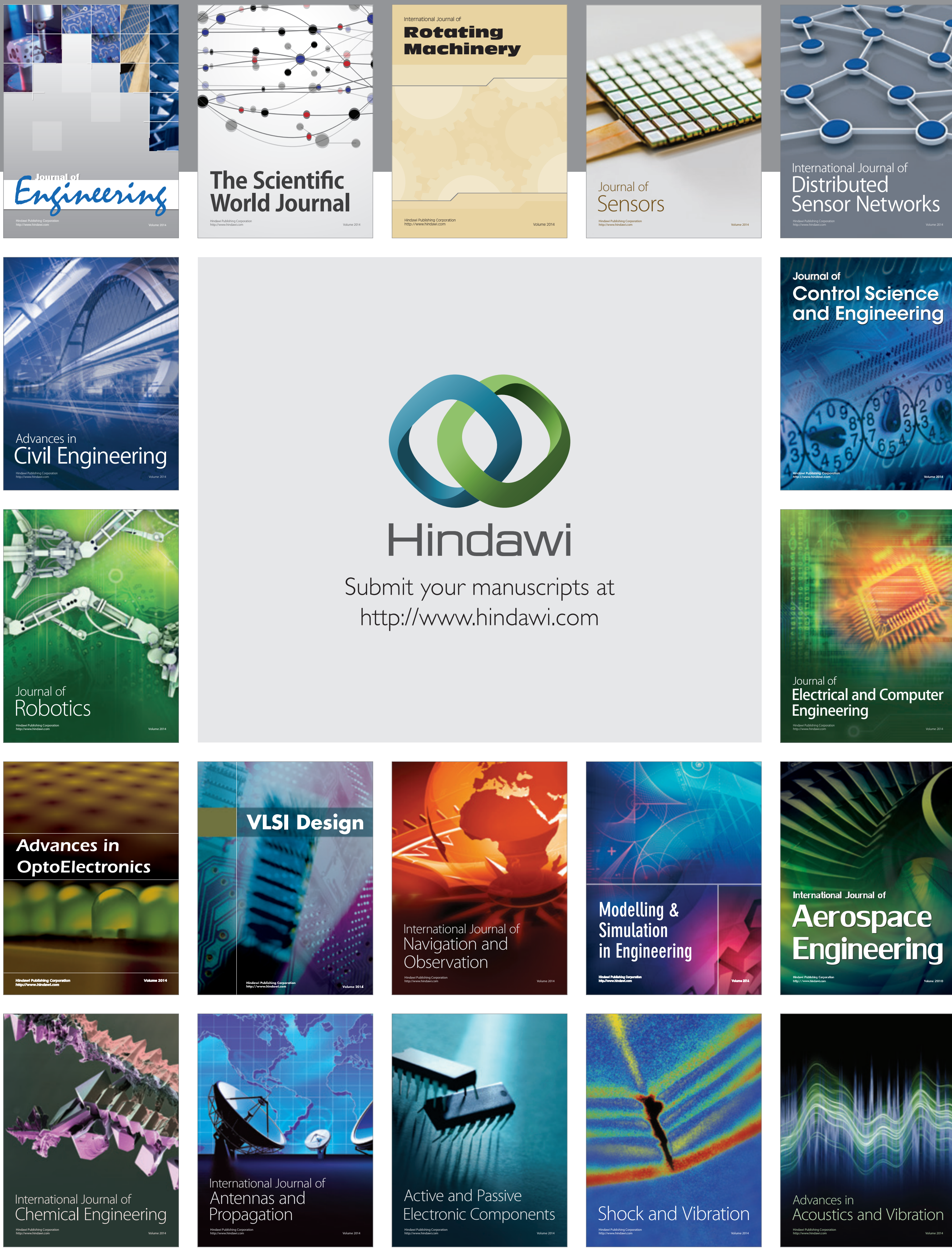
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