A study of tensile residual strength of composite laminates under different patch-repaired series

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Abstract. The tensile behavior of composite laminate structures repaired by bonding external patches was studied in the paper. Two different types of patches including wedge patches and inverted wedge patches were used and failure mechanisms, failure load and strength predictions were studied. A convenient and fast method of building 2-D finite element modeling (FEM) of laminate structure repaired was proposed and the strength of repaired laminate structures was calculated by FEM. The results showed that more than 80% tensile strength of the undamaged laminate could be recovered by bonding patch repairs. Moreover, the results indicated that the strength of inverted wedge patches repair were higher than that of wedge patches repair. FEM simulation results indicated that high stress concentration was found along the edges of invert patches and the most weakness part located in the adhesive bondline. FEM analysis results showed that the strength predicted matched well with the test strength.

1. Introduction

The composite has been widely used in aerospace so far. However, there are some repair questions to be solved due to damage caused by accidental impact, hailstones, bird strike and lightning strike. [1-4] Thus, the better repair techniques and processes for composite components are needed to be studied. Many different composite repair techniques have been used to repair different types of damages in composite components with different geometric construction. And one of those was bonding repair. For bonding repair, a load carrying repair must be adopted for intact aerodynamic contour of composite components in a permanent repair of structure damaged.[5-7] Relevant experiments about composite material repair were in progress. Campiho *et al*[8] developed interface finite elements model based on the indirect use of fracture mechanics and studied the effects of the single and double-lap repairs on the bearing load strength of composite materials by using the ABAQUS software. The reported results indicated that the strength of the adhesives affects immensely on the failure mode, whereas its fracture toughness exhibit a little influence. Oztelcan *et al*[9] focused on developing appropriate test specimens to evaluate computationally and experimentally the effects of static and cyclic loads on the strength of a composite blade with a repair site and a local finite element model with the appropriate boundary conditions was proposed. Kumar *et al* [10] analysed the failure modes

of bonding repaired laminate structure under tensile loading. Test results revealed that failure occurred into two modes including fracture and pull-out of fibre and cohesive shear failure of the adhesive film. Breitzman *et al* [11] examined the strength of the composite repaired under tensile loading with and without overlay plies. The results showed that the patch stacking layers affected greatly the strengh recover of the laminate and the strength could exceed 80% of the undamaged laminate by using overlay piles. The performance of a repaired structure using adhesive bonding depends not only on the adhensive properties, bonding mode and fracture mode, *et al*, but also on the patch shape design and adequate shape of bonding patch was in need of designing in order to ensure maximum repair efficiency. [12-13] To our knowledge, there were few systemic reports on effects of patch shape design on strength recover in bonding repair. In addition, the FEM models proposed by previous researcher were complex, which was not suitable for fast calculation with high precision.

In the study, bonding repair with two different patches including inverted wedge and wedge patches was used to repair composite laminate damage and effects of patch types on the tensile residual strength were discussed. In addition, a convenient and fast 2-D FEM was also proposed to predict the strength of composite components repaired. These researches favour to increase the repair efficiency and minmize the repair cost for composite components.

2. Experiments

In the external patch technique, considering bending strains due to eccentric load path, the patch must be capable of withstanding the high peel and shear stresses which develop at the edges of the overlap of patches. [14-15] In the experiments, two types of patches made up of prepreg were shown in **Fig. 1.**
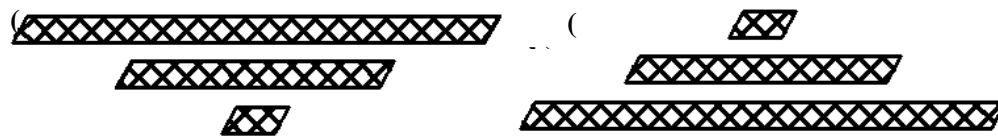

Fig. 1 The diagram of two different patches with three layers: (a) SeriesI:Wedge prepreg patch; (b) SeriesII:Inverted wedge prepreg patch

A useful data base on specimens repaired by wedge prepreg patch under tensile loading has been prepared in previous work. [16-19] It showed that the required mechanical performance could be achieved by the repair method of using wedge prepreg patch. This study extended to repair surface damage by inverted wedge prepreg patch and analyze the repairing effect. The stacking sequences of laminates used in this work were followed: [45/0/0/45], [45/0/45/0/45] and [45/0/45/0/45/0/45]. The schematic of repaired specimens was shown in **Fig. 2**.
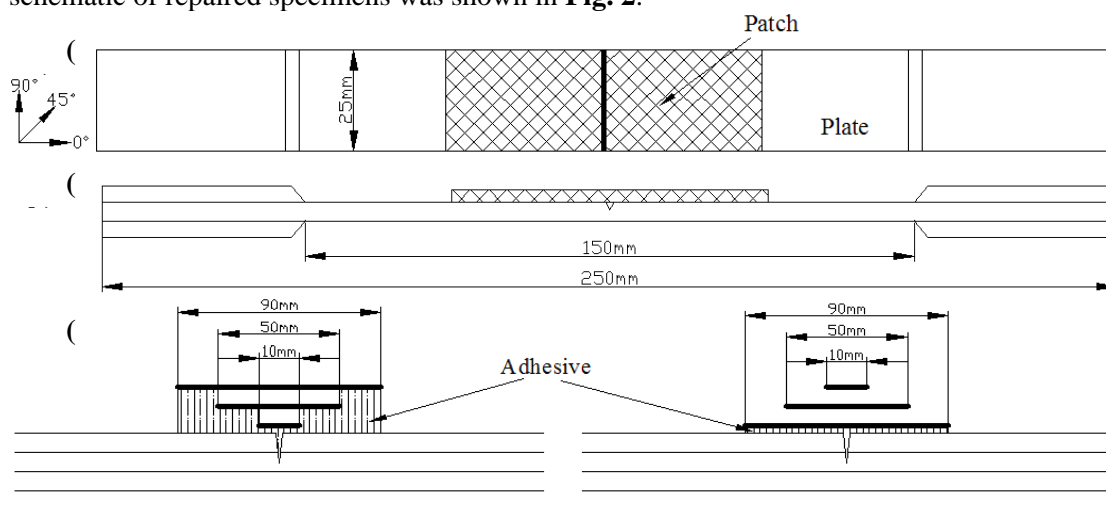

Fig. 2 Test specimens: (a) Front view; (b) Side view; (c) Two different of repaired details

Fig. 2(a) and (b) showed two layers scratch were made in the middle of the specimens (250×25×0.285n, n means layers) and then the rectangle patches were used to bond one-sided of the specimen. Beveled Al plates (25×50×2mm) were bonded to each end of the test specimens. All patches for repairing specimens were designed according to following stacking sequence: [0/0/45] and outermost 45° layer increased the impact resistance performance and minimized cracking. After repairing, C-Scans were performed on all of the repaired specimens to evaluate the quality of component repaired. The tensile tests were operated at room temperature on a MTS universal test machine and five specimens were tested for each configuration specimens. The beginning load and the maximum load were set at 0kN and 100kN, respectively. Load speed was 2% of maximum load.

In this work, a convenient and fast 2-D modeling was built in order to analyze the strength of repaired plates by using MSC.Patran with MSC.Nastran solver. The mesh pattern around the patch was kept very fine in order to capture the high stress and the failure concentration. Boundary conditions were simulated by fixing one end and applying a continuing stage loading in the longitudinal direction at the other. The adhesive bondline was simulated as being isotropic. The patches and the plate were meshed using the Quad-4 node elements. With [45/0/0/45] stacking laminate as example, its symmetrical structure was divided vertically. As shown in Fig. 3(a), A, B, C and D four parts were designed as different stacking layers and the finite element grid connected in turn. The entire model built was shown in Fig. 3(b).
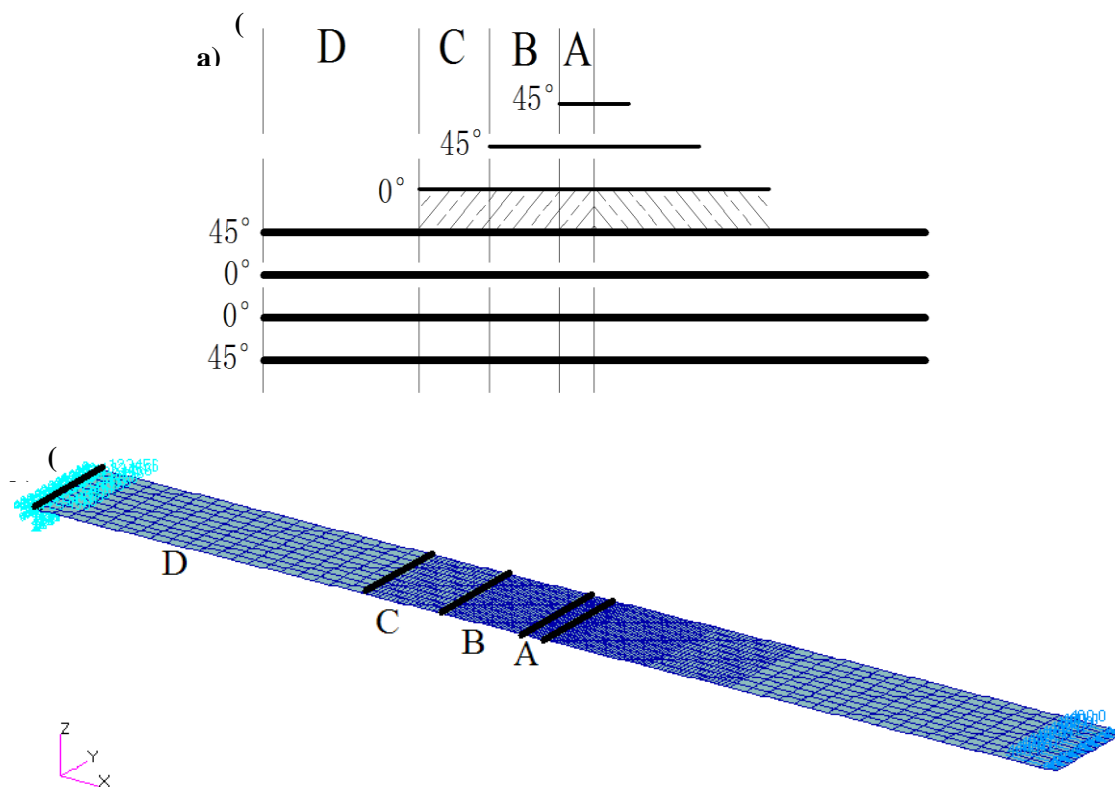

Fig. 3 Finite element model of repaired plate

3. Results and Discussions

3.1 Fracture surface observation

In the experiments, the sound of fiber broken off could be heard. The fracture surfaces were examined by low magnification photography in order to analyze the failure mechanisms of patch repairs. For the undamaged specimens, a large amount of fibre breakage and delamination could be seen near the fracture **Fig. 4(a)** . In addition, it could be observed that fracture located in the weak section of the

plates. The specimens repaired with two different patches were shown in **Fig. 4(b)** and **Fig. 4(c)**. The fibre breakage, delamination and patches separations can be observed in the location of damage plate. Failure process was as follows. [10] Firstly, the adhesive was particularly damaged, and then whole patch separated from parent plate under bearing the tensile load which exceeded the maximum shear load of the adhesive. Meanwhile the stress concentrating formed in the location of scratch and scratch extended into deeper section of the laminate, and then final failure occurred.
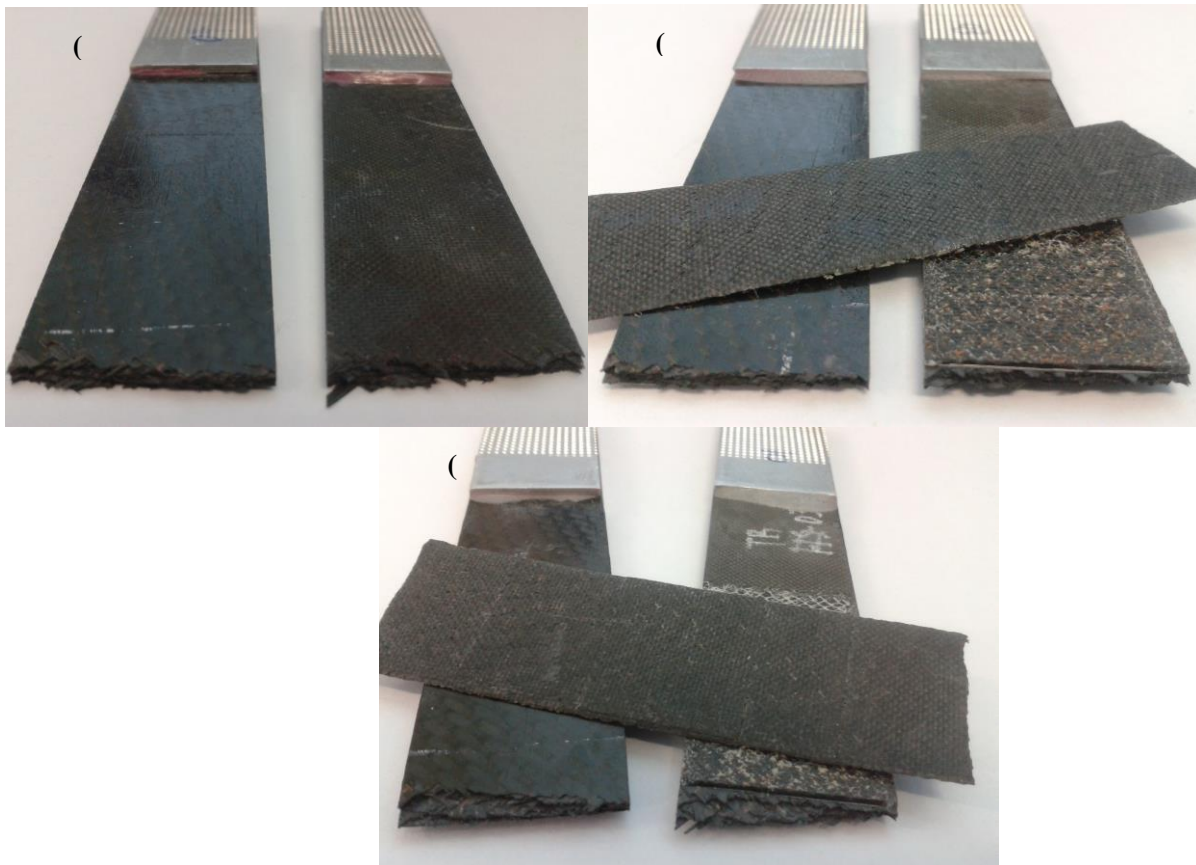

Fig. 4 Photographs of failed specimens: (a) Good specimens; (b) Specimens repaired with SeriesI; (c) Specimens repaired with SeriesII

3.2Analysis of load and displacement curves
Load and displacement curves of specimens with three types of stacking sequences were shown in **Fig. 6** and tensile loads of failure were listed in Table. 2. It could be observed from **Fig. 6** that the strength of unrepaired specimens changed in a linear fashion at different loading and their failure loading were about 13kN, 17kN and 24kN, respectively. For repaired specimens, the similar linear behavior could also be seen before failure. For laminate structure repaired by wedge patch, the upper large patch stacked on the lower small patch, which resulted in the forming of a wedge angle (**Fig. 6**) at the end of pre-patch. When repaired laminate structure bore load, the patch fractured layer by layer, not fractured as a whole, which was fit for bearing large load. However, there was not a wedge angle in invert wedge patch and the loaded repaired laminate structure with invert wedge patch fractured integrally. Thus, the laminate structure repaired by Series II could bear a little higher tensile loading than that of series I. The data listed in **Table. 1** showed the tensile strength of composite laminate repaired by series I and series II methods could recover 80% strength of the undamaged laminate, which indicated that Series I and Series II were used practically in bonding repair.
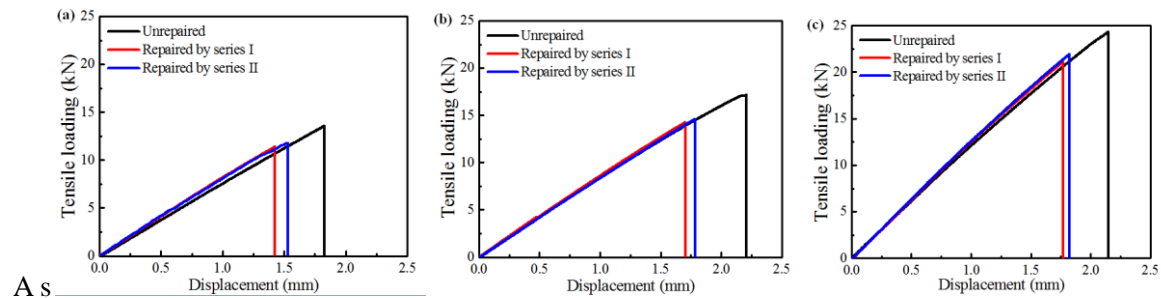
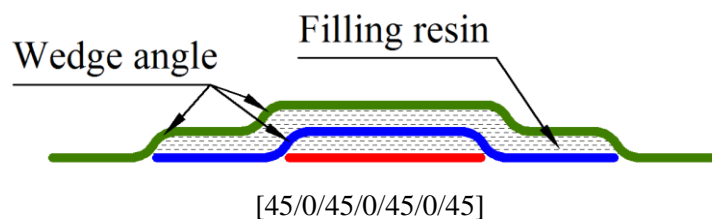**Fig. 5** Load and displacement of specimens: (a) [45/0/0/45]; (b) [45/0/45/0/45]; (c)

Fig. 6 Wedge angle in wedge patch

Table 1 The tensile failure load (KN)

Specimens	[45/0/0/45]	[45/0/45/0/45]	[45/0/45/0/45/0/45]
Undamaged	13.61	17.17	24.37
Repaired by SeriesI	11.48	14.30	21.12
Repaired by SeriesII	11.77	14.63	21.96

3. 3 Strength prediction of patch repairs

As for the composite components, Maximum stress criterion was applied to predict Maximum load of damage initiation as defined in the following equation:

$$\sigma_1 = X_t, \ \sigma_2 = Y_t \ \text{and} \ |\tau_{12}| = S \qquad (1)$$

If $\sigma_1 > X_t$, $\sigma_2 > Y_t$ or $|\tau_{12}| > S$, damage will occur.

For repaired laminate, this criterion could get maximum load of damage initiation, but the real damage modes of repaired structure was not described clearly by it.

The finite element analysis was carried out by applying a 2-D modeling. **Table. 2** gave the prediction of strength value in each modeling. It could be seen that the strength values of repaired modeling were lower than those of the undamaged parent material. According to the phenomenon of the test results, it could be concluded that the adhesive was the weakest part in the repaired structure. For laminate structure repaired, the adhesive strength should be analyzed used the FEM. **Fig. 7** and **Fig. 8** gave the FEM results of the maximum stress of the adhesive bondline.

Table 2 The prediction of strength value (KN)

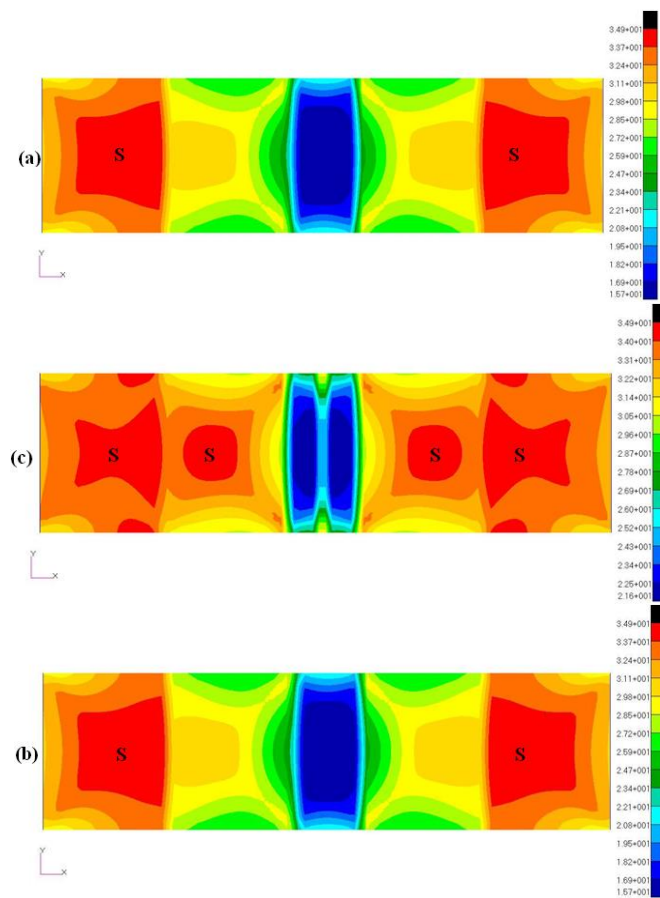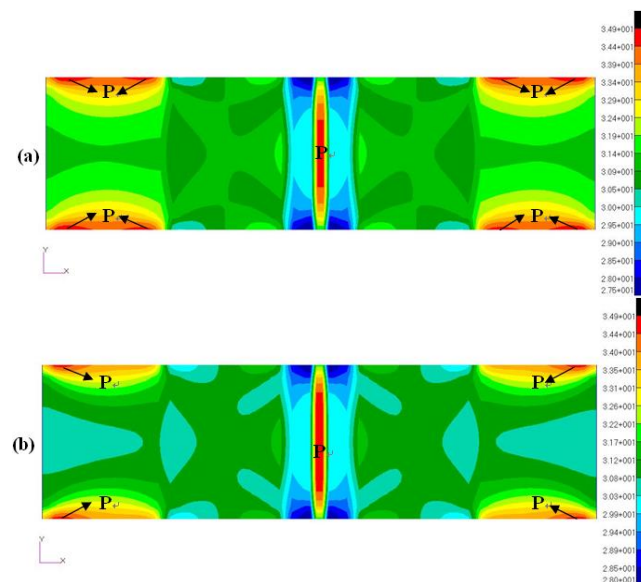| Modeling	[45/0/0/45]	[45/0/45/0/45]	[45/0/45/0/45/0/45]
Undamaged	12.36	15.63	23.60
Repaired by SeriesI	11.14	14.06	20.83
Repaired by SeriesII	11.46	14.37	21.61

Fig. 7 The maximum stress nephogram of the laminate repaired with wedge patch: (a) 4 layers; (b) 5 layers; (c) 7 layers
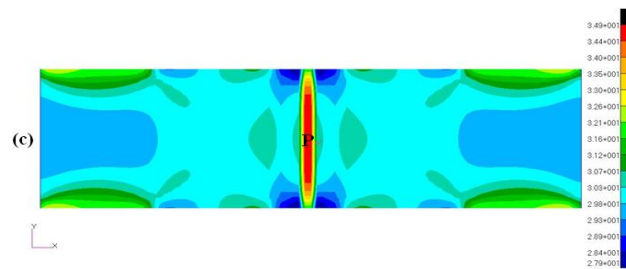
Fig. 8 The maximum stress nephogram of the laminate repaired with inverted wedge patch: (a) 4 layers; (b) 5 layers; (c) 7 layers

It could be seen from **Fig. 7** that both ends of adhesive bondline (S area in Fig. 8) were the weakest location in the laminate repaired with wedge prepreg patch. The bearing stress extended to the middle part with the increasing in layer thickness and the stress concentration was formed near the damage position. The repaired structure failed when the adhesive bondline reached its maximum bearing stress. It could be seen from **Fig. 8** that the weakest part of the repaired structure with inverted wedge prepreg patch located in the edge of adhesive bondline (P area in **Fig. 8**). The edge stress concentration could be observed in four layers laminate and it decreased with the increasing in layer thickness. The repaired structure failed when the adhesive bondline reached its maximum stress. In a similar study, Liu [20] studied the effects of patch stacking sequences on the fracture process and showed that cohesive damage initiated in the bondline close to the longitudinal patch edges where the stress focused. In addition, patch stacking sequences had a great impact on the strength of laminate. [21]

The FEM results and the test results are shown in **Fig. 9**. It could be seen that the strength were on the rise with the increasing layer stacking thickness, and the FEM results matched the test results well.
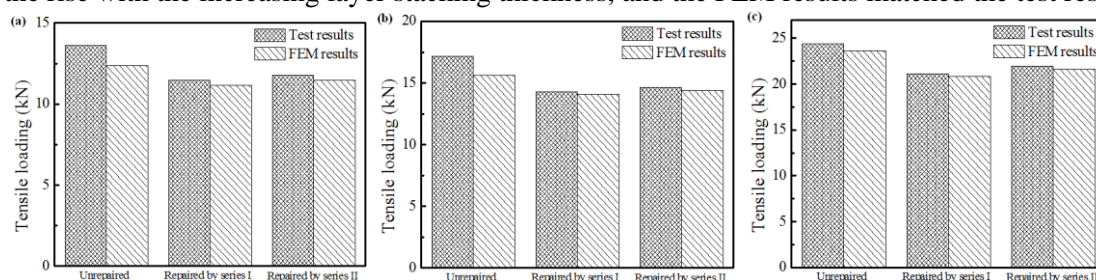

Fig. 9 *Compare of the test results with the FEM results: (a) [45/0/0/45]; (b) [45/0/45/0/45]; (c) [45/0/45/0/45/0/45]*

4. Conclusion

In the paper, the scratch laminates were repaired by patch-bonding with wedge patch and inverted wedge patch. The effect of composite patch type and layer thickness on the strength of laminate repaired was studied and a 2-D model was purposed to predict the repaired strength results. The conclusions were summarized as follow.

 (1) The tensile strength of laminate plate after repair could recover more than 80% with wedge patch and inverted wedge patch. In addition, the tensile strengths were 11.46KN, 14.37KN and 21.61KN by using inverted wedge patch and they were a little bit higher than that of wedge patch repair.

(2) By analyzing the stress nephogram, patch type affected stress distribution and stress concentration place. The stress focused on the edge of patch by inverted wedge patch repair and it concentrated in the center area along the vertical direction of patch by wedge patch repair.

(3) The repaired FEM was built and results showed that the simulation was in good agreement with experimental data, which could be used in quick calculate of repaired structure in an emergency.A subsubsection. The paragraph text follows on from the subsubsection heading but should not be in italic.

Acknowledgements

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