INFLUENCE OF EXTERNAL PATCH SHAPE AND LOCATION ON THE LOW-VELOCITY IMPACT BEHAVIOR OF REPAIRED CFRP LAMINATES

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Introduction

Carbon fiber reinforced polymer (CFRP) laminates are increasingly investigated for lightweight engineering applications due to their inherently excellent mechanical properties. Local damages on CFRP laminates, which are usually caused by low-velocity impacts, lead to the reduction in local mechanical properties of the composite structures. It brings the need to repair the structures rather than replacement at first place to reduce the maintenance cost of CFRP laminates. Therefore, the development of external patch repair technique is in high demand.

Preparation of repaired specimens

Carbon fiber/epoxy composite laminates T300/7901 with the stacking sequence $[(0/90)_3]_S$ having the dimension of 150 mm × 100 mm × 3.6 mm were used as the parent plates. Circular holes with the radius of r = 3 mm were cut on the different locations of these parent plates using water-jet cutting as the accidentally caused damage. These damage locations are 0 mm, 10 mm, 20 mm, 30 mm and 40 mm from the center of the parent plates, respectively. Geometry information of the parent plates is given in Fig. 1.

The damaged laminates are repaired using single external patches, which were manufactured from the same CFRP laminates but with stacking sequence of [0/90/0], and the thickness is 0.45 mm. Patches were prepared with four different shapes: (i) circle, (ii) square, (iii) hexagon and (iv) octagon. In the test plan, the patches with circle shape were manufactured with radius $R = 2r$ (where r is the hole radius). The square, hexagon and octagon patches were prepared with same area A = 113.10 mm^2 which equals to the circle one. A toughened single part epoxy adhesive with a controlled 0.15 mm thick bond line was used to repair the damaged parent plates with different patches.

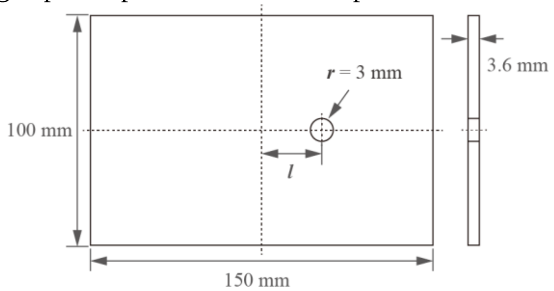

Fig.1 Geometry information of the damaged plate.

Drop weight impact test

A drop-weight impact test was designed according to the ASTM D7136/D7136-07 standard, in which the repaired specimens were placed over a flat support with a 125 mm × 75 mm rectangular cut-out, as shown in Fig. 2a. This cut-out allows the impactor to contact through the specimen without interferences. Additionally, on the support fixture, four rubber clamps ware used to restrain the test specimen during the impact.

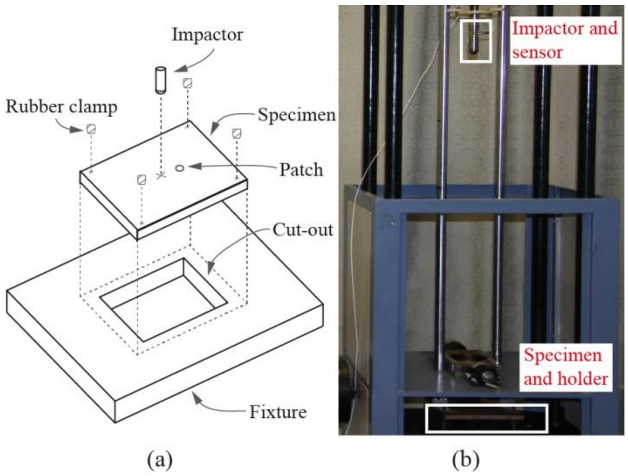

Fig.2 Schematic illustration of the drop-weight impact testing system and (b) the apparatus used in the experiments.

The hemispherical impactor, whose weight is 2.5 kg and radius is 25 mm, is placed at the initial height of 0.54 m to perform low-velocity impact tests (see Fig. 2b). An anti-impact device was used over the fixture to avoid secondary impact on the repaired specimen. During the impactor dropping process, it assumes that there is no energy loss due to friction, so that the impact velocity and energy are computed as 3.25 m/s and 13.20 J, respectively. For each specimen, a maximum force was reached before the impactor penetrated through the specimen. The onset of impact is defined by the sudden increase of impact force in the force-time curves.

Numerical simulation

3D FE models of repaired specimens were built using Abaqus/Explicit software. All specimens and related components of the test were meshed with eight-node 3D solid, reduced integration elements. A meshed FE model, which includes a circle patch with radius $R = 2r$, is shown in Fig. 3. In this model, the circle patch is located at 20 mm from the center of repaired specimen. A group of cohesive elements are used to simulate the interface between the parent laminate and patch. Boundary conditions were simulated by fixing all DOEs of the fixture base and rubber clamps. The velocity of 3.25 m/s along the vertical direction was imposed on the impactor.

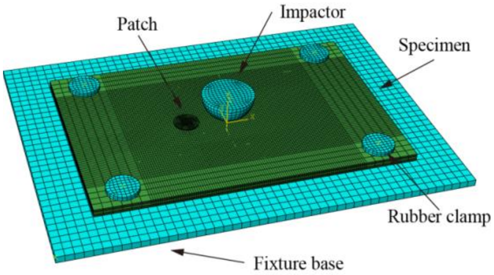

Fig.3 Numerical model of the drop-weight impact test corresponding to the specimen repaired by a circle patch.

To predict the intralaminar damage initiation and the final failure of composite laminates repaired with patches, 3D Hashin failure criteria has been employed in the numerical simulation. Failure behavior of the adhesive bondline between damaged laminate and patch is described using a cohesive zone model (CZM).

Results and discussion

In order to validate the simulation methodology, numerical models were built based on the drop-weight tests for repaired specimens with circle and hexagonal patches. The related numerical drop-weight tests were performed. The predicted and experimental time history curves of the impact force and energy are shown in Fig.4. It clearly indicates that, there exists almost no difference in the maximum impact energy and its corresponding time.

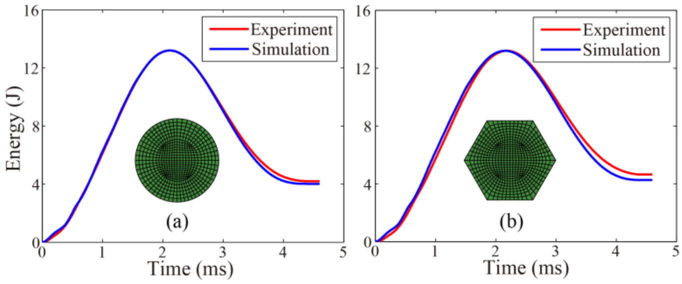

Fig.4 Experimental and predicted impact energy history curves of repaired specimens with (a) circular and hexagonal patches as a function of time.

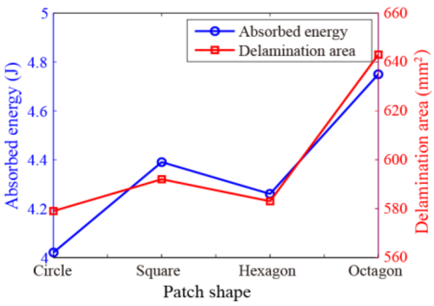

Fig.5 Predicted curves of absorbed energy and delamination area of specimens repaired with different patch shapes.

The influence of external patch shape on the repair performance was studied by performing numerical simulation of specimens repaired with different patch shapes. The curves of absorbed energy and delamination area of specimens repaired with different patch shapes were obtained from numerical predictions, as shown in Fig. 5. It is found that, the specimen repaired with circle patch, absorbs the relatively minimum impact energy (4.02 J). Similarly, the related delamination area caused by the impact, was 579 mm^2, which is also the lowest value compared with other cases. Therefore, it concludes that the circle patch is the optimal choice to repair the damaged laminate with hole.

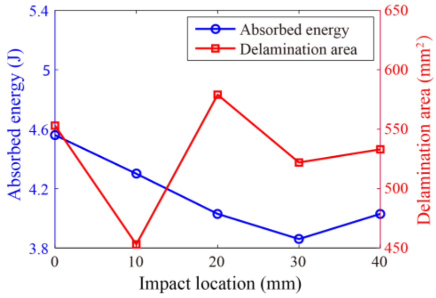

Fig.6 Predicted curves of absorbed energy and delamination area of repaired specimens impacted on different locations to the damage.

Additionally, the circle patch design was used to repair the parent plates in which the damages locations are different to the center of the specimens. Fig. 6 illustrates the predictions of absorbed energy and delamination area of repaired specimens impacted on different locations. In term of the absorbed impact energy, impact location of 30 mm from the center of the repaired specimen reveals the relatively small damage. However, from the tendency of the delamination area curve, the case corresponds to the impact location of 10 mm from the center of the repaired specimen, the impact causes less serious damage (delamination area of 453 mm^2). The difference of these two curves is probably contributed to different penetration depth of impactor into the repaired specimens.

Conclusions

Low-velocity impact behavior of repaired CFRP laminates has been investigated experimentally and numerically. Various patches of different shapes were used to repair damaged specimens on the different locations to the impact point. Impact response such as impact force and energy, has been recorded from experimental measurement and numerical simulation. The influence of external patch shape and location on the improvement of impact resistance caused by the repairing patch was analyzed according to the delamination surface area and absorbed energy of the repaired laminates using numerical simulation. From the comparison of delamination area and absorbed energy, it is found that, the circle patch leads to a better repair performance. For the impact location distance, when the impact occurs on the point 30 mm from the center of repaired specimens, less energy is absorbed during the impact process. While the minimum delamination area appears when the impact location is 10 mm from the center of the repaired specimen.

References

[1] Y. Tie, Y. Hou, C. Li, X. Zhou, T. Sapanathan and M. Rachik: An insight into the low-velocity impact behavior of patch-repaired CFRP laminates using numerical and experimental approaches, Composite Structures, 2018, 190:179-199.