EXPERIMENTAL INVESTIGATION OF VIBRATION BEHAVIOR OF PATCHED COMPOSITE PLATES

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SUMMARY: In this paper, the vibration behavior of a clamped edge-cracked composite plate repaired by composite patching was investigated. Modal testing was first used to measure the natural frequencies and mode shapes of the composite plate before and after repair. The amplitude fluctuation electronic speckle pattern interferometry(AF ESPI) was also employed to find the real-time absolute whole-field displacement. Based on the results from those two methods, effects of different stacking sequences and numbers of layers of the patching on the vibration behavior of the composite plate were studied. It was found that the change of fiber orientation and the number of layers of the patching have more significant influence on the variation of mode shapes of higher modes.

KEYWORDS: composite patching, modal testing, amplitude fluctuation ESPI

INTRODUCTION

Due to its high specific strength and stiffness, composite material has been widely used in various flying vehicles. Occasionally, defects are found in the structural components. When defects are not critical enough to make the replacement of the components, patching is one of the best ways to extend the structural life and reduce maintenance expenses. Baker and Jones[1,2] first introduced the concept of bonded repair. They formulated the theoretical derivations and discussed experimental aspects of various bonded repair methods. Rose[3,4] carried out the repair by adhesive bonding of the isotropic and orthotropic materials with crack. Chiang, et al.[5] first employed the speckle technique to determine the stress intensity factor of a side-cracked aluminum alloy sheet patched by the fiber-reinforced composite material.

Very limted research work has been done on the vibration characteristics of the patched components. Wang and Lin[6] experimentally investigated the vibration of a composite plate containing a circular hole repaired by composite patching. The fiber orientation of both the composite plate and patching is the same. They found that the anti-vibration capability of the composite plate may be weakened for higher mode after certain type of patching is applied.

In this paper, the amplitude fluctuation electronic speckle pattern interferometry(AF-ESPI) was used to investigate the vibration behavior of a clamped edge-cracked $[0]_{16}$ composite plate repaired by composite patching of three different stacking sequences and two different numbers of layers. The whole-field displacement was obtained and integrated with the results obtained by the modal testing.

AMPLITUDE FLUCTUATION ELECTRONIC SPECKLE PATTERN INTERFEROMETRY [7, 8]

Traditional video-signal-subtraction method was still used in the AF-ESPI, however, the reference image is in vibration state instead. The corresponding brightness displays on the monitor can be expressed as

$$B_{IM} = \frac{4N\alpha\beta\pi}{\omega}[J_1^{\,2}(k)\cos^2\varphi]^{1/2} \tag{1}$$

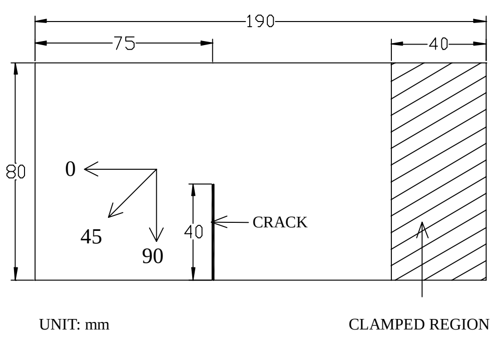
where N is the number of vibration period during CCD’s exposure time, α and β are constants, ω is vibration frequency, $k = \eta A$, $\eta = 2(1+\cos\theta)\pi/\lambda$, λ is the wavelength of laser light source, A is the vibration amplitude, φ is the random phase resulting from surface roughness, and J_1 is first-order Bessel function. Fringe lines are represented when Eq. (1) is zero, so if there is a set of number ζ_i^*, and all the number $k=\zeta_i^*$ will make Eq. (1) become zero. Then the vibration amplitude can be expressed as

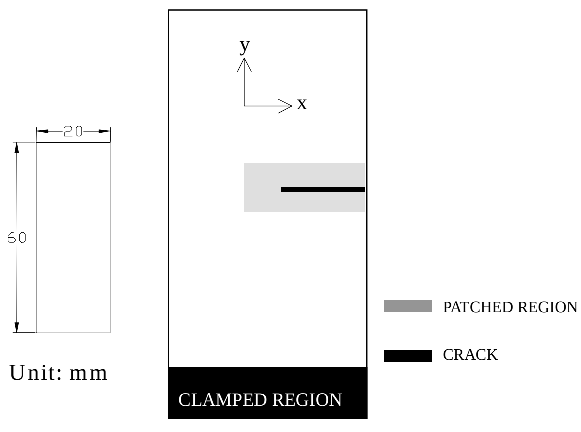
$$A = \frac{\lambda\zeta_i^*}{2\pi(1+\cos\theta_0)} \tag{2}$$

In this paper, He-Ne laser was used, its wavelength is 632.8 nm and θ_o is 12.72^o.
The AF-ESPI can provide better image resolution and narrower fringe width, hence better contrast and higher sensitivity.

SPECIMEN

In this paper, two kinds of specimen were prepared. The first kind is the unpatched composite plates, one uncracked and one cracked, used for comparison purpose. The second kind is the patched composite plates by applying the composite patching on the edge-cracked composite plates. The type of the composite material for both the composite patching and plate is carbon fiber reinforced plastic(CFRP) (Toho Rayon Co., Japan). All composite plates are unidirectional and 16 layers, i.e. $[0]_{16}$. The adhesive for applying the patching was mixed by 1:1 ratio of 5 Minute Epoxy and 5 Minute Epoxy Hardener(Devcon Co., U.S.A.).
Along one side of the composite plate’s long edge, a crack of 40mm length and 0.35mm width was cut. The unpatched cracked plate’s shape and dimensions are shown in Fig. 1. Three different stacking sequences of patching were adopted, i.e. [0], [0/90] and [±45]. Two different numbers of layers of the patching were used, i.e. 4 and 8. Dimensions and region of the patching are shown in Fig 2.
Fig. 1 Dimensions of unpatched cracked plates Fig. 2 Dimensions and region of the patching





EXPERIMENTAL SETUP AND PROCEDURE

Modal Testing

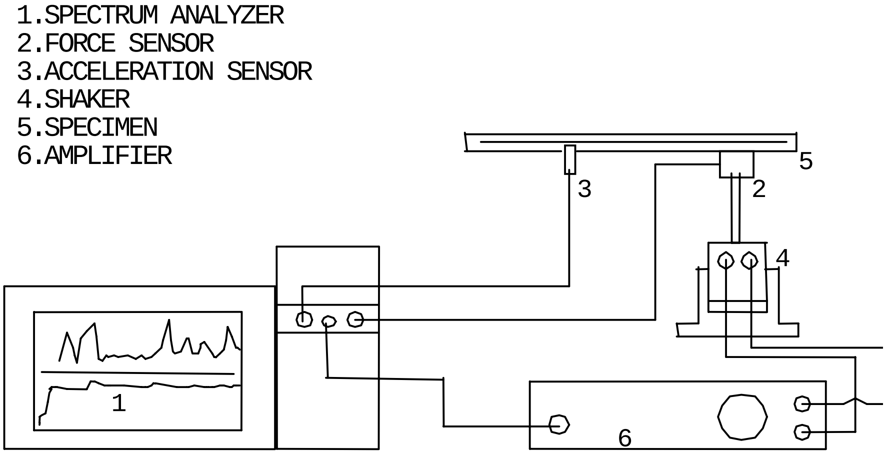
The experimental setup of the modal testing method is shown in Fig. 3. The specimen was first clamped on one side by a table vise, and sampling points were drawn on the back of the plate. The specimen, table vise, shaker, power amplifier and spectrum analyzer were placed on an optical table. The force sensor on the shaker was adhered on the specimen and the accelerometer was consecutively moved to every sampling point to record the acceleration signal. The shaker's signal is pseduo random noise supplied by the spectrum analyzer. The transfer function of each sampling point was calculated by the spectrum analyzer. Using the analysis software, STAR[9], to operate these transfer function values, the mode shape of each natural frequency was obtained. The mode shape at the largest amplitude was drawn by the software, SURFER[10].

AF-ESPI

The experimental setup of the AF-ESPI system is shown in Fig. 4. The experimental procedure of the AF-ESPI is as follows:

(1) The specimen was clamped the same way as in the modal testing. The specimen's surface was sprayed a layer of white powder to reflect the light uniformly.
(2) The optical system was setup to measure the out-of-plane displacement. A 35mW He-Ne laser was used as the light source, the mirror was used to change laser beam's direction. The laser beam enters the single-mode optical fiber by a coupler. Furthermore, the laser beam was separated into an object beam and a reference beam by a beam splitter. The object beam illuminated the specimen directly and then reflected into the CCD camera. The reference beam was reflected by a beam splitter and then entered into the CCD camera.
(3) The function generator provides the sine wave at one of the natural frequencies determined from the modal testing. Using this signal, the shaker applied a load on the specimen and the average force was measured by spectrum analyzer and force sensor.
(4) An image was first captured and stored into the memory of the image-processing board as a reference image. Then the reference image was subtracted from the next captured image. The subtracted image was saved and then modified by the look up table, converted into gray level and displaced on the screen.

Fig. 3 Modal testing setup



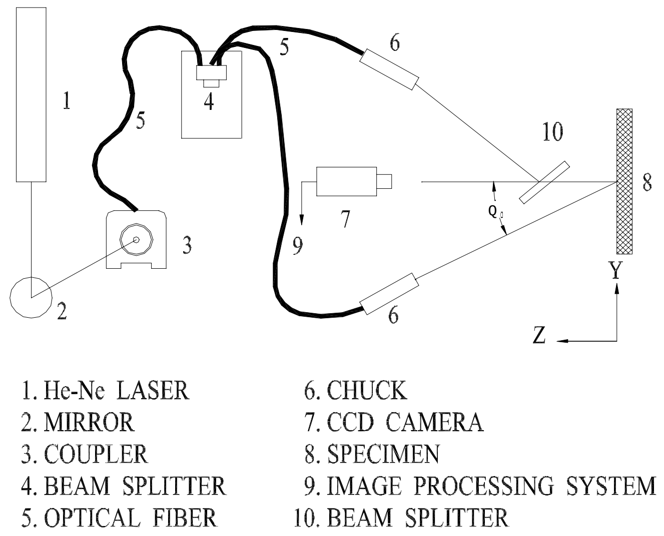


Fig. 4 The ESPI setup

RESULTS AND DISCUSSIONS

Mode Shapes and ESPI Fringe Patterns

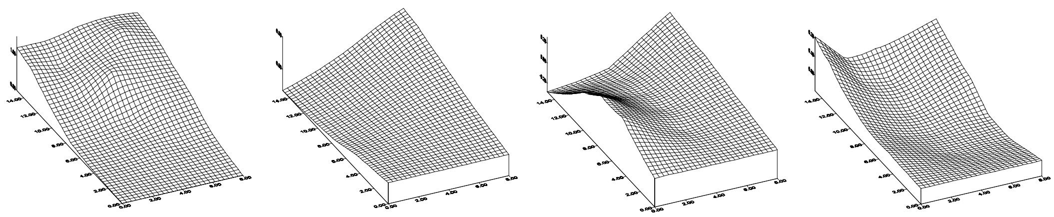
Figs. 5 and 6 as well as Figs. 7~14 are mode shapes and ESPI fringe patterns of the first to fourth modes obtained from modal testing and AF-ESPI, respectively. The A-A in the ESPI fringe patterns represents the clamped edge. The number shown in the fringe patterns represent fringe order. The positive and negative signs beside the number represent that the displacement is out-of-phase. The ESPI fringes represent the distribution of the absolute constant displacement.

About the mode shapes of the first mode, results of uncracked plate show that it is a bending mode(Figs. 5(a) and 7(a)), and the unpatched cracked plate(Figs. 6(a) and 8(a)) shows that the fringes are oblique above the crack. This is due to the free surfaces of the crack. Bending moment M_y about the longitudinal axis was caused about the crack, i.e. two bending moments are in effect on the region above the crack. The other one is the bending moment about the clamped end, M_x.

For the mode shapes of the second mode, the mode shape of the uncracked plate is a twisting mode and almost symmetrical with respect to the longitudinal axis(Figs. 5(b) and 7(b)). There are almost no fringes below the crack for the unpatched cracked plate(Fig. 8(b)), which means the displacement is very small in this region. Above the crack the fringes are parallel with the longitudinal axis. For the uncracked plate, both the bending moment about the clamped end M_x and the torque about the longitudinal axis, M_{yx}, are acted. For the unpatched cracked plate, the fiber was cut and therefore, the right-hand side of the plate has no capacity to resist moment M_x, i.e. only M_{yx} is in effect. So the fringes are parallel with longitudinal axis. Mode shapes of the first and second mode after repairing(part (b) of Figs. 9~14) are similar to those of uncracked plate. No significant difference is noted.

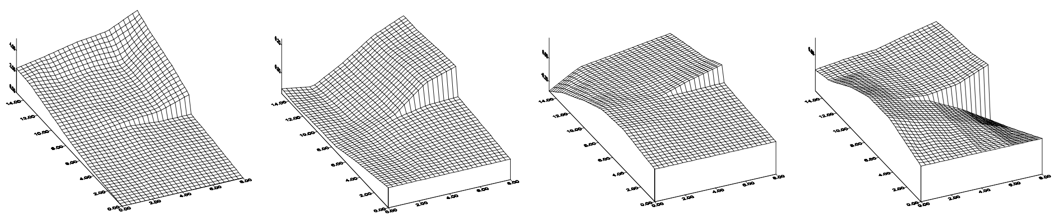
Large difference of the mode shape can be clearly observed for the third mode between the uncracked and unpatched cracked plates(Figs. 5(c) and 6(c)).The companion ESPI fringes(Figs. 7(c) and 8(c)) obtained from the modal testing shows that both the left and right sides of the uncracked plate(Fig. 5(c)) are lifted. In addition, the top region of the plate is sagged. On the other hand, the region above the crack is lifted and then inclined down and

toward the top left corner of the plate of the unpatched cracked plate(Fig. 6(c)). The ESPI fringe patterns for the third mode of patched plates are shown in part(c) of Figs. 9~14. Comparing those fringe patterns with that of the unpatched cracked plate(Fig. 8(c)), the distribution of fringes located at the top left region is always denser than that at the right region. The number of fringes, however, remains almost the same as the case of unpatched cracked plate. On the contrary, the number of fringes at the right region is reduced after patching. This change of the fringe distribution could be due to the change of the mass redistribution after patching. Since the patching area is only around the crack, i.e. the mass reinforced effect is occurred only in this area. At the same time, the mass of the top left region remains almost the same before and after repair. It is very interesting to point out that the disappearance of fringe patterns for the lower left region of the plate after applying [0/90] patching (Figs. 13(c) and 14(c)). The fashion of the fringe distribution is almost the mirror image of the fringe patterns of mode 2 for the unpatched cracked plate.
As for the mode shapes of the fourth mode of the uncracked plate, indentation is occurred at the center and the top half region is lifted(Figs. 5(d) and 7(d)). By simply observing the ESPI fringe patterns of the unpatched cracked plate as shown in Fig. 8(d), one may be disguised by the continuity of the fringes across the crack and mistakenly thought that the vibration across the crack is in phase. Mode shapes obtained from the modal testing(Fig. 6(d)) clearly help one to identify that out-of-phase vibration is occurred across the crack. Hence, a tearing effect is acted on the crack. Among the four modes, the fourth mode has the strongest tearing effect. As can be obviously seen from the part (d) of Figs. 9~14, this out-of-plane tearing effect could be significantly improved after the patching is implemented.
As to the effect of different numbers of layers of the patching on the mode shapes, it is clear that no significant difference can be found from both modes 1 and mode 2 for all the three stacking sequences. In addition, the fringe patterns remain almost the same for the third mode of the case of [0/90]. For the third mode of the cases of [0] and [±45], the range of the fringe pattern is extended and the order of the fringe is reduced only in the region to the right of the nodal line. The distribution fashion of the fringe patterns of the mode 4 is greatly simplied for all the three stacking sequences.



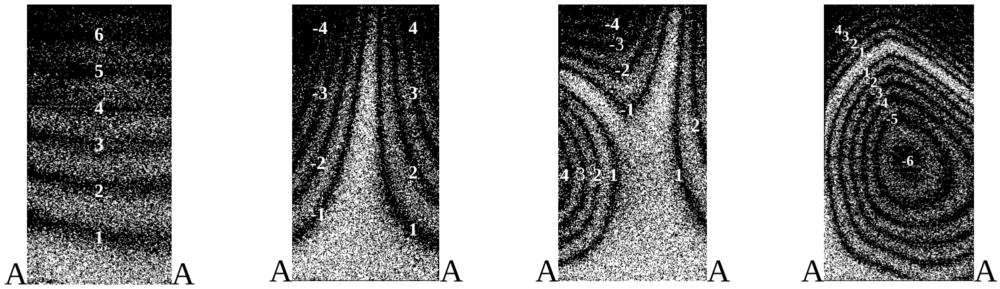
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 5 Mode shapes of uncracked plate



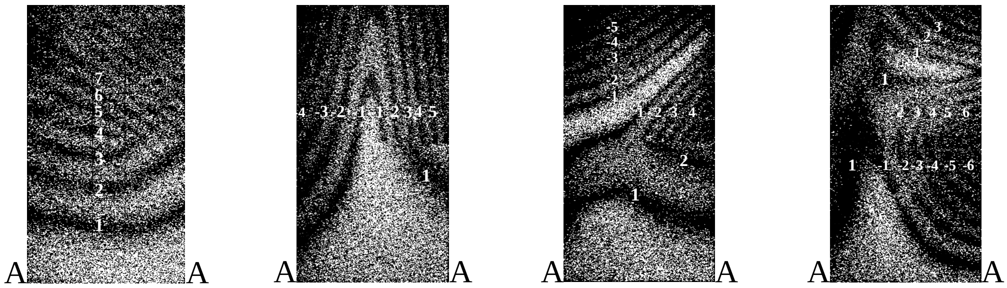
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 6 The mode shapes of unpatched cracked plate



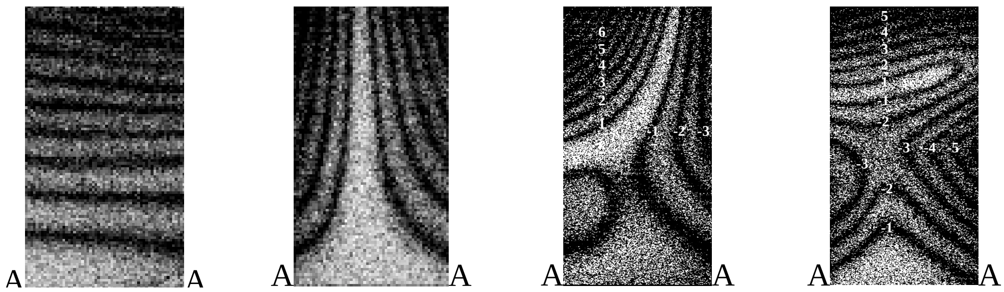
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 7 ESPI fringe patterns of uncracked plate



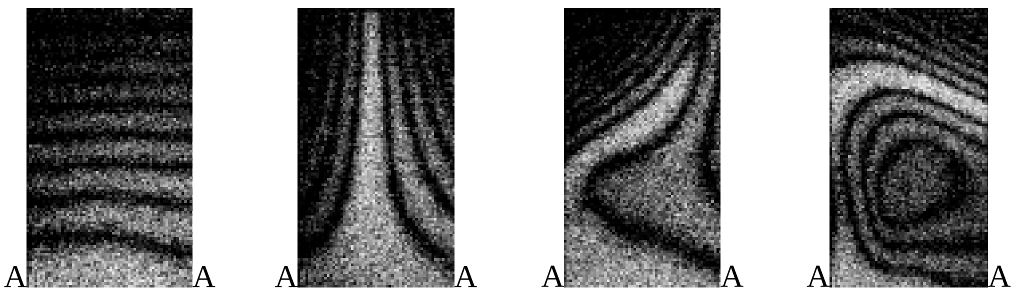
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 8 ESPI fringe patterns of unpatched cracked plate



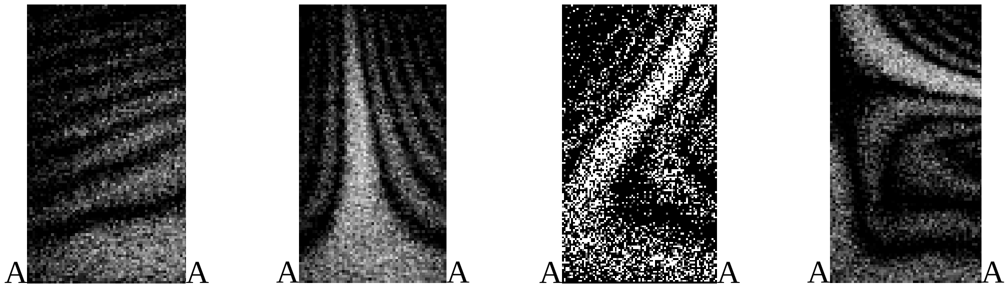
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 9 ESPI fringe patterns of $[0]_4$ patched plate



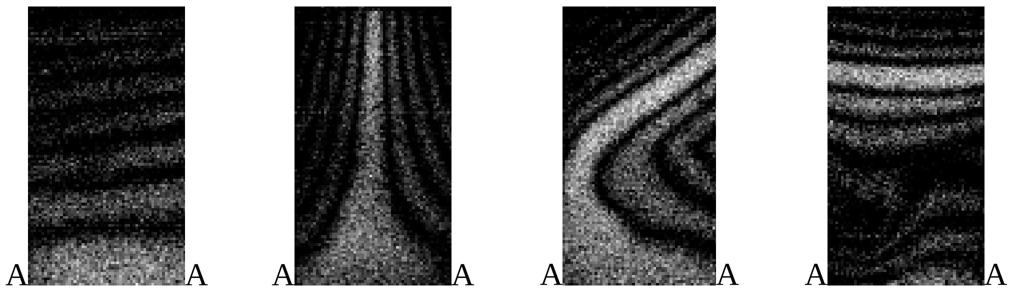
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig 10 ESPI fringe patterns of $[0]_8$ patched plate



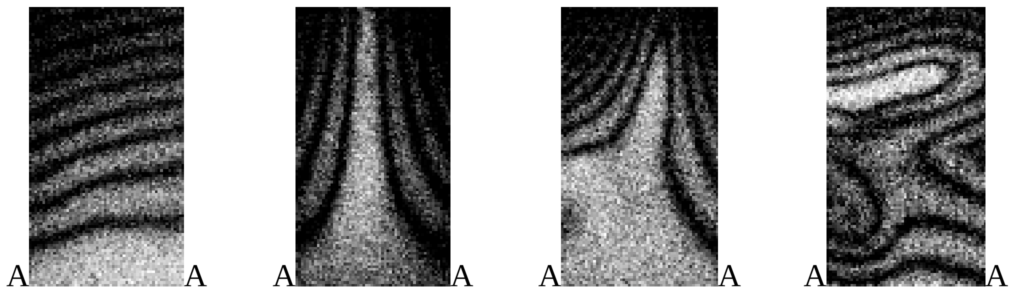
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 11 ESPI fringe patterns of $[\pm45]_4$ patched plate



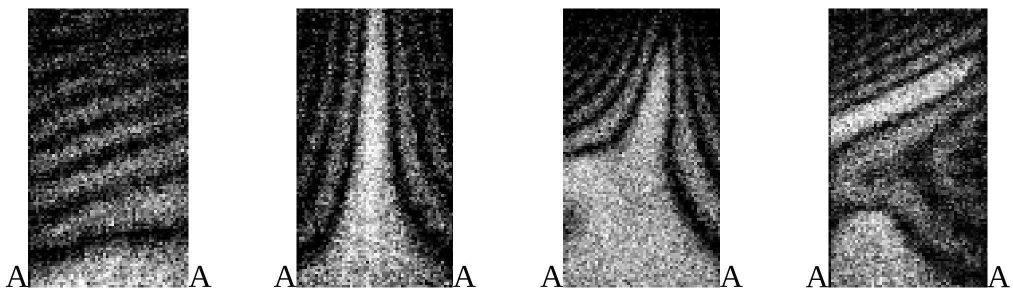
(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig 12 ESPI fringe patterns of $[\pm45]_8$ patched plate



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 13 ESPI fringe patterns of $[0/90]_4$ patched plate



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Fig. 14 ESPI fringe patterns of $[0/90]_8$ patched plate

CONCLUSIONS

Modal testing and AF ESPI were employed in this paper to investigate the vibration behavior of composite plate before and after composite patching of three different stacking sequences and two different numbers of layers. The patching indeed alleviates the crack effect for the cases investigated. For higher modes(mode 3 and 4), the effect of variation of stacking sequences and numbers of layers on the mode shapes is more significant. Based on the results reported by Wang and Lin[6], however, the anti-vibration ability may be weakened by patching for certain mode of the specimens. Therefore, it is not overemphasized when structural components containing defects were repaired, the change of the vibration characteristics after repair should be seriously evaluated to prevent superfluous work.

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