INTEGRITY MONITORING OF COMPOSITE PATCH REPAIRS USING FIBER BRAGG GRATING SENSORS

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Abstract

The existence and growth of internal impact damage in a composite laminate or a crack in a metallic specimen induced complex strain fields. These strain fields will affect the reflected spectra of fiber Bragg gratings (FBG) embedded in the composite laminate or stuck on a metallic specimen, enabling the development of the defects to be monitored. When such damaged structures are repaired by composite patching, FBG can also be embedded in the patch. The continual development of the underlying defects will cause distortion and shift in the reflected spectrum when a load was applied. Thus with the help of the FBG sensors, we can evaluate the integrity of the patch bonding and monitor the development of an internal damage after a repair.

Introduction

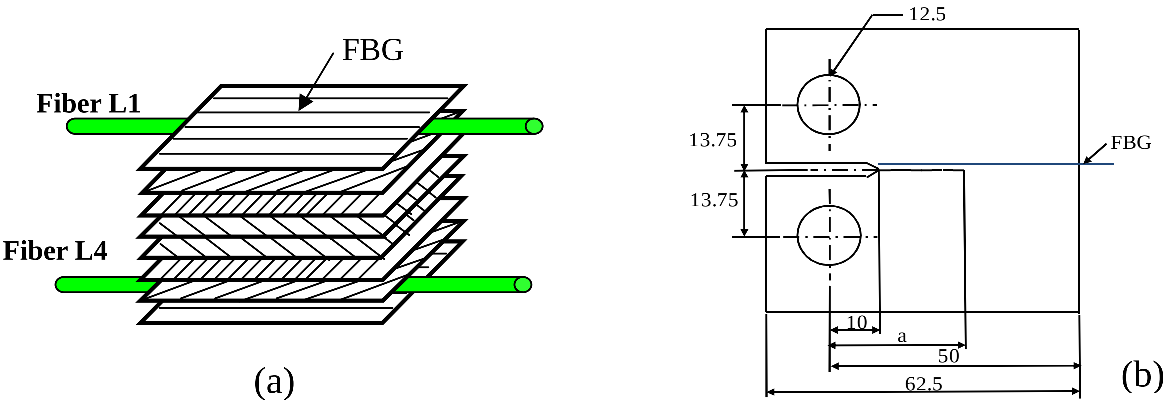
With the aging of the commercial aircraft fleet, damage such as fatigue, corrosion will accumulate in the highly stressed metal parts. The increasingly employed composite parts is more resistant to fatigue and corrosion but is susceptible to impact damage due to bird strike, tool drop and hail storm as well as lightning damage. These damages will induce insidious defects such as delamination, debonding and matrix cracking [1] that may ultimately develop into catastrophic failures. In both cases, suitable repair is needed to improve safety and reliability. Adhesively bonded composite repairs have become increasingly popular and they have many advantages over conventional mechanically fastened repairs. For example, they do not induce new stress concentration hole; have high specific stiffness and strength enabling weight and thickness reduction and are readily formed into complex shapes, permitting the repair of irregular components. However, the inspectability and durability are two major concerns of bonded repairs. Currently, no non-destructive testing technique can reliably check the repair integrity and effectiveness. Moreover, moisture and temperature will degrade the composite patches so that the underlying defects may resume growing after some time.

We propose to use FBG sensor to monitor the development of underlying defects after composite patching repair in metallic and composite specimens. Optical fiber sensors and in particularly FBG are finding increasing applications in structural integrity monitoring [2-5]. They have a small diameter, long fatigue life and may be embedded inside the composite patch without adverse effect on its properties and have been shown to be able to monitor impact event occurrence [6, 7] and detect impact damages in composites [8, 9].

2. Experimental procedures

2.1 Specimens preparation

Both composite and metallic specimens have been employed. Composite laminates were made from T300/3501 Graphite/Epoxy prepreg stacked in the sequence [0/45/90/-45]s and cut into specimen coupons (200mm×25.4mm×1mm). FBG sensors were embedded in the two outer 0^o laminae along the axial loading direction (Fig.1a). The fiber on the side that faces the impact is designated L1 and the one on the back surface L4. Each of the fibers was offset by 3mm from the center-line of the specimen. The fibers are led into the specimen coupon at one side and terminate inside the specimen at some distance short of the gripping position at the other side. The metallic specimens (Fig.1b) were fabricated from SCG400 steel plate of thickness 2mm. A single FBG was stuck close to and parallel with the future crack path. FBGs were fabricated in a Ge–B co-doped single mode fiber by side writing using a phase mask with a period of 1.05 μm. The sensing length of the FBGs was about 10 mm. The reflectivity of the resulting FBG was about 99%. The peak wavelengths and the FWHM (full width half maximum) of the FBGs were ~1550 nm and ~ 0.175 nm respectively. The reflected spectra from the FBGs were interrogated periodically using an Anritsu optical spectrum analyzer (MS9710C OSA).



(a) (b)

Fig. 1 (a) Lay out of the prepreg stacking and the embedded optical fiber sensors in the composite specimen; (b) Schematic of the metallic CT specimen and fiber sensor.

2.2 Impact and fatigue testing

For the composite specimens, impacts were made at the center of the specimens using a 90g aluminum falling weight from a height of 140cm with an apparatus that conforms to ASTM D5628. After impact the coupons were subjected to cyclic loading from 1.4kN-14kN at a frequency of 4.5Hz using an MTS servo-hydraulic test machine. Ultrasonic C-scan was also employed to examine the impact damage before and after the fatigue test. The metallic specimens were loaded between 0.15-1.5kN at a frequency of 5Hz. Crack length was measured with a traveling microscope to a resolution of 0.01mm. The reflected spectra from the FBGs were recorded periodically.

2.3 Composite patch repair

A test was interrupted after cyclic loading for a certain amount of cycles following an impact when C-scan examination detected a growth of the delamination damage. The specimen surface facing impact was polished with 2000mesh sand paper and cleaned with acetone. A

$[\pm 45]_{2S}$ patch of the same Graphite/Epoxy prepreg was applied and cured. The length of the four layers of prepregs are respectively 50, 48, 46 and 44mm to alleviate stress concentration at the edges of the patch. Additional FBGs, one on the interface between the specimen and patch (RD), one at the mid-thickness of the patch (RM) and one on the outer surface of the patch(RU), were installed. To avoid matrix regions, RD and RM are in the $+45^{o}$ (same direction as the graphite fibers) while RU is parallel to the loading direction (Fig.2a). On the outer surface of the patch, a fiber sensor RU has also been stuck along the centerline.
For the metallic specimens, after fatigue crack propagation for about 10mm, the tests were interrupted and one surface of the specimen was polished and cleaned. A [90/0/90] Graphite/Epoxy prepreg patch measuring 60mm×40mm was applied over the crack using LOCTITE X-272942 adhesive. A series of 4 FBGs parallel to the crack were placed on the first layer of the patch. The first FBG is directly over the crack and the remaining FBGs are each 1.5mm apart from each other, as shown in Fig.2b. The patch was then cured in an autoclave. In both the composite and metallic specimens, cyclic loading was resumed and the reflected spectra from the FBGs were recorded periodically as before.

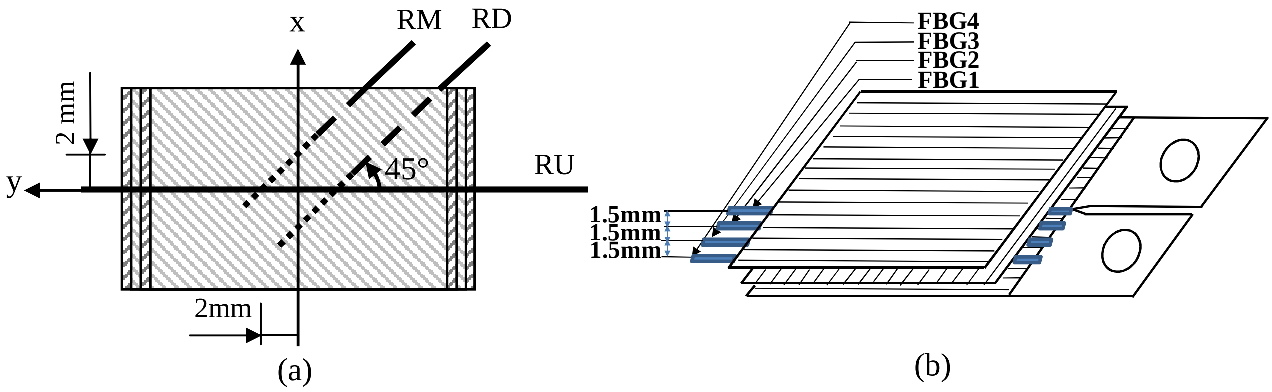


Fig. 2 Schematic of the composite repairing patches and the corresponding FBGs for (a) composite specimens; (b) metallic specimens.

3. Basic properties of fiber Bragg grating sensors

When broadband light is coupled into an optical fiber with a uniform Bragg grating, a single peak with wavelength λ satisfying the Bragg diffraction criterion will be reflected while the other wavelengths will be transmitted through:

$$\lambda = 2 n_e \Lambda \qquad (1)$$

where n_e is the effective refractive index and Λ is the periodicity of the grating. If the uniformity of the grating period is perturbed by a strain field, the single peak reflected spectrum will broaden or chirped. λ typically shifts by ~1pm under a strain of $1\mu\varepsilon$.

4. Results and Discussion

4.1 Effect of Impact and fatigue on FBGs in the composite specimens

Fig.3 shows the FBG spectra just before and after impact for the fibers L1 and L4. Originally each of the FBG spectra has a single sharp peak. On embedding, curing and cutting into testing coupons, a shift in peak wavelength together with slight widening and splitting of the peak occurred as is evident in the solid lines in fig.3. This may be attributed to residual stresses that arose during the composite fabrication process. After the impact damage, the original peaks widened even more and split heavily into a number of distinct peaks. The above phenomena are more prominent in the spectrum from the L1 fiber. Such a change in the spectra suggests the strain distribution along the FBG has changed from roughly uniform to highly non-uniform. The latter is probably caused by the impact induced internal defects that have perturbed the residual stress field near the FBG.

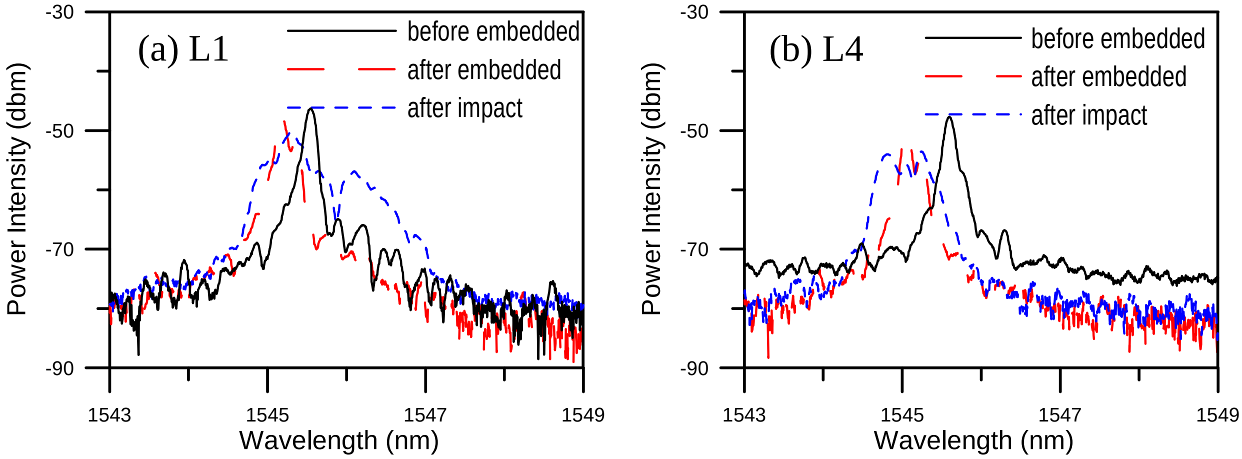
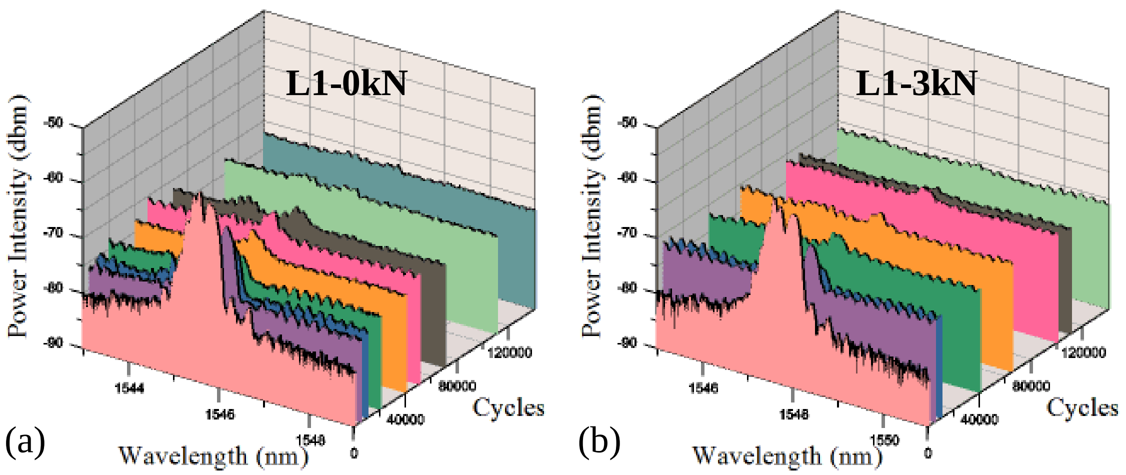


Fig. 3 Comparison of FBG spectra before and after embedded in CFRP as well as after an impact from fiber sensor (a) L1, facing impact and (b) L4, at the far side from the impact position.

Fig.4 shows the development of the spectra measured at 0kN and 3kN with the loading cycles. As loading cycle increases, the peak intensity gradually falls while the background intensity rises in both L1 and L4 spectra. Such development is more marked in the L1 spectra than that in the L4. Raising the loading from 0 kN to 3 kN not only shifts the spectra to the longer wavelength but also aggravates the above peak submerging phenonmenon. By 40000 cycles, the peaks have practically disappeared under a loading of 3kN in the L1 spectra. C-scan results (Fig.5) show that at 50000 cycles after impact, the delaminated area has enlarged and extended to the edge of the specimen. If cyclic loading was continued, complete failure of the specimen would occur at ~140000cycles. In some specimens, test was interrupted to carry out patch repairing.



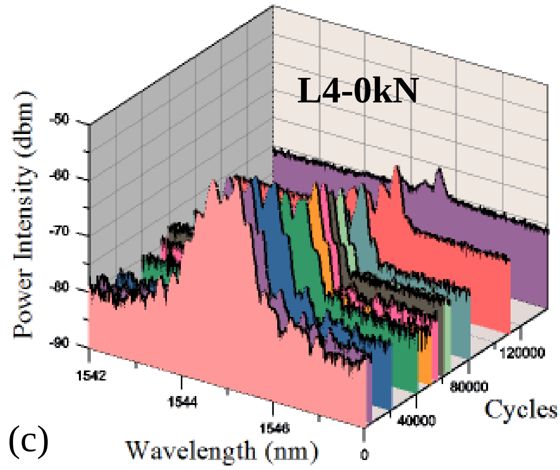


Fig. 4 Development of FBG spectra with fatigue loading cycles for: (a) L1 at 0 kN; (b) L1 at 3 kN; (c) L4 at 0 kN; (d) L4 at 3 kN.

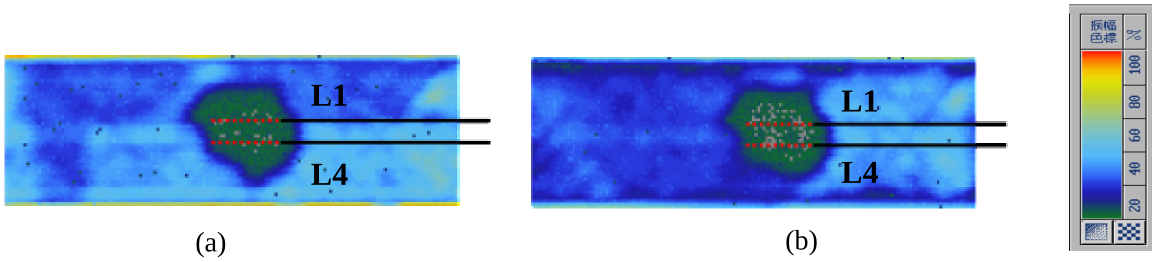


Fig.5 C scan results of the composite specimen (a) just after impact; (b) 50000 cycles after impact.

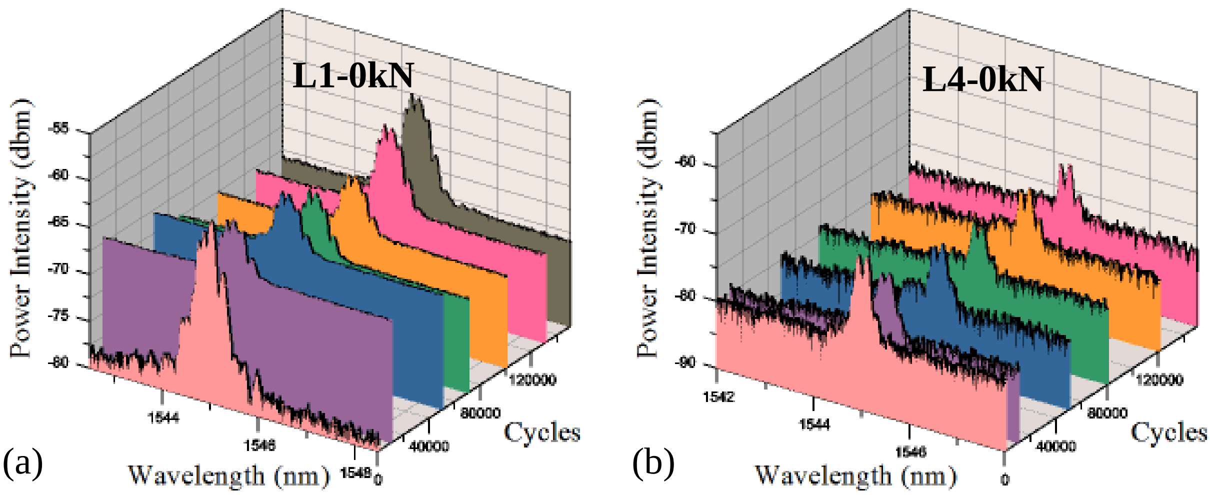


Fig.6 Development of the FBG spectra under 0 kN with fatigue cycling after patch repair from: (a) L1; (b) L4.

4.2 Effect of patch repair on the composite specimens

Just after curing of the repairing patch, the peaks in the FBG spectra have recovered significantly (Fig.6). However, on resumption of fatigue cycling, the background intensity quickly increased initially and then the whole spectra stabilized. Such a condition persisted to 150000 cycles while the specimen still remained intact, suggesting the internal impact damage has stopped growing. The spectra of the fiber sensors on the patch preserved a sharp narrow peak. The shift of these peak wavelengths with applied loading after different loading cycles are shown as series of curves in Fig.7 for each FBG. During the initial 10000 cycles, a marked vertical up-shift of the curves occurred, indicating a permanent extension of the specimen under cyclic loading shortly after repair. This up-shift slowed down and settled to a more or less steady state after 30000 cycles. This initial up-shift corroborates with the initial change in the reflected spectra from the embedded FBGs in L1 and L4. Thus both the signal from the FBGs inside the specimen and that in the repairing patch may be used to indicate whether the growth of an internal impact damage has been successfully stopped by the patch repair. On the other hand, the slope of wavelength shift against load reflects the compliance of the specimen. This compliance is slightly smaller at low load but increases to a constant value at higher load. Such a change probably reflects the existence of an initial slight curvature in the specimen as the patch was applied on one surface. On loading, it flexes and straightens, giving a smaller compliance. Thereafter it deforms along the loading direction and the slope reflects the axial stiffness of the specimen. For each fiber sensor, the series of curves have essentially the same constant slope, indicating the stiffness, and hence the integrity of the patch and its adhesion to the specimen, has remained intact during the subsequent fatigue cycling.

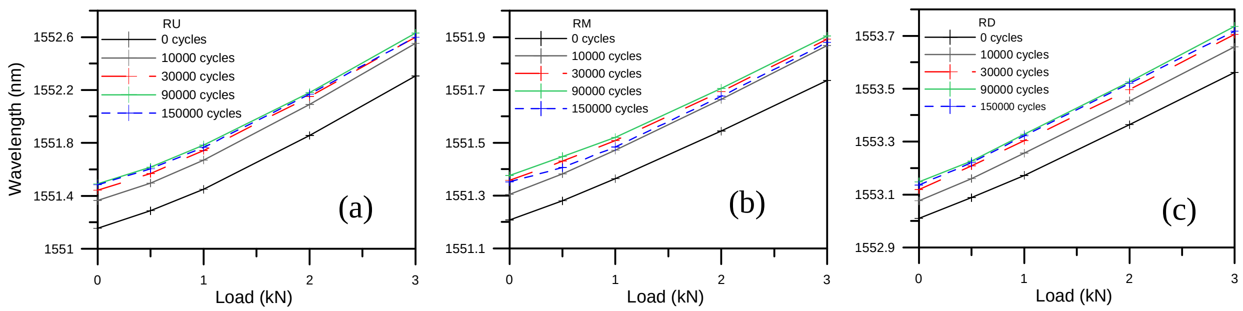


Fig.7 Peak wavelength shift with applied loading after different number of fatigue cycling from FBG in (a) RU; (b) RM and (c) RD.

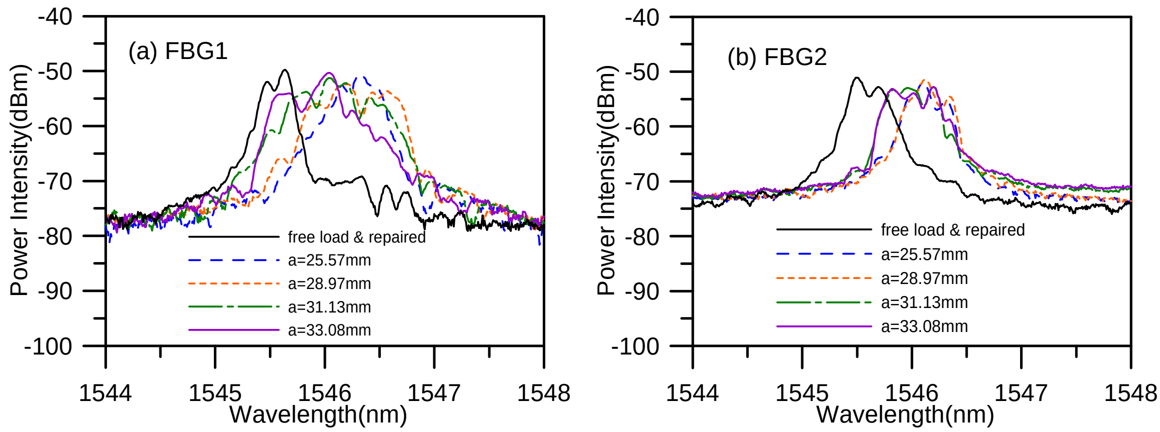


Fig.8 Change in the FBG spectra with crack length from FBG embedded in the composite repairing patch. (a) FBG1 was directly above the crack; (b) FBG2 is 1.5mm from the crack.

4.3 Effect of fatigue crack growth on the FBGs on the metallic specimens

In the metallic specimens, the spectra of an FBG stuck parallel to a fatigue crack preserve its sharp narrow peak until the crack tip plastic zone spans a certain portion of the grating. Then broadening and shifting of the peak occurred while the peak intensity dropped. This is true whether the FBG is on a bare metallic specimen or inside a repairing patch straddling a crack. Fig.8 shows the case for the latter situation. It also shows that when the FBG was further away from the crack, change in the spectra is less sensitive to crack growth as the influence from the crack tip plastic zone is weaker (see Fig.8b). When loading amplitude is decreased after patch repair to achieve a crack arrest condition, the FBG spectra also remain unchanged

(Fig.9). Besides using the change in shape and wavelength of the spectra to monitor the development of a fatigue crack, the intensity of the highest peak in the spectra can also be employed. Fig.10a shows the peak intensity decreases continuously in a specimen when the fatigue crack is continuously growing. The initial sharper drop corresponds to a crack before patch repair. After repairing, crack growth rate decreased while the peak intensity showed a series of up and down. The spectra and peak intensity of the FBG embedded inside the patch is under the influence of both the residual stress in the patch and the underlying crack tip stress zone. The rise and fall in the peak intensity is attributable to the interaction between the crack tip field and the residual stress. When the crack has arrested, the peak intensity remained essentially constant (Fig.10b).

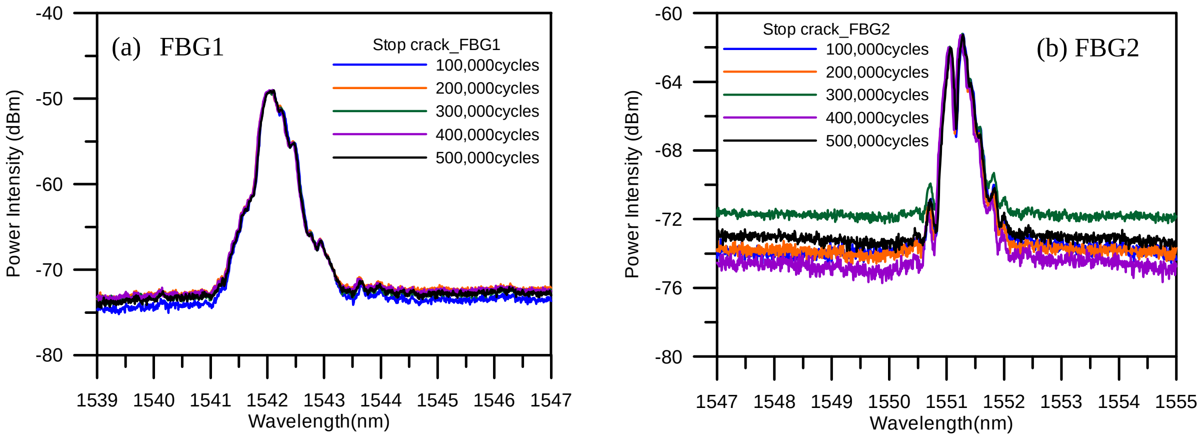


Fig.9 Development of the FBG spectra from FBG embedded in the composite repairing patch when the crack has been arrested. (a) FBG1 was directly above the crack; (b) FBG2 is 1.5mm from the crack.

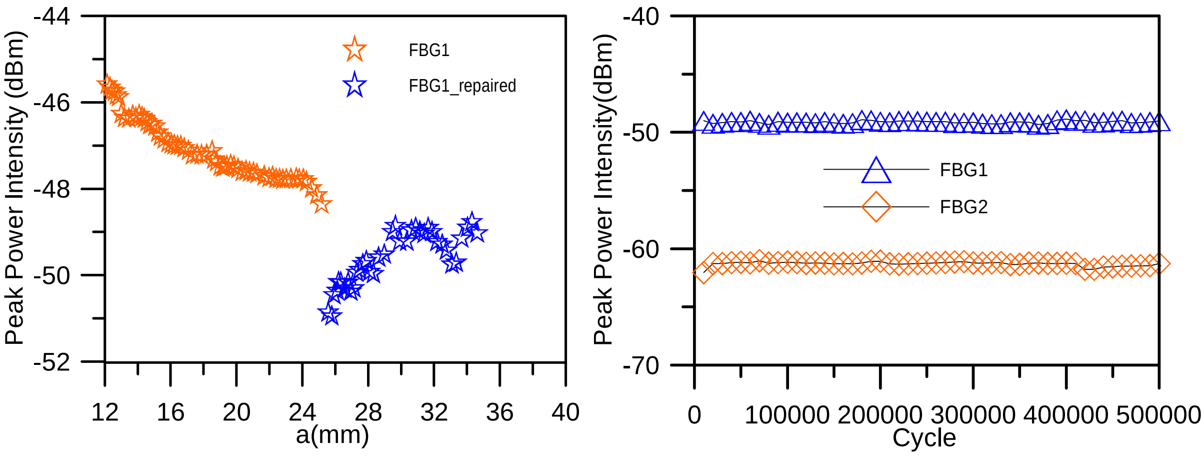


Fig. 10 The change in peak intensity of the FBG spectra when (a) a continuously growing crack before and after repair; and (b) an arrested crack.

5. Conclusion

Fatigue cracks and impact damage spots were created in the metallic and composite specimens respectively with optical fiber sensors installed. The characteristic Bragg spectra will change when the impact damage was created. Spectrum shape would also change when the impact damage or the crack in the metallic specimen developed under fatigue loading.

After a patching repair, if the underlying impact damage or crack was still progressing under cyclic loading, the characteristic spectra of the FBGs originally installed in the specimens would continue to be distorted. Even if there was no prior installation of fiber sensors, FBGs can be embedded in the repairing patch and by monitoring the patch compliance through the peak wavelength shift versus applied loading curve, it is possible to tell whether the underlying damage has stopped developing.

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