Inspection of Kissing-bond Defect in Honeycomb Structure by shearography

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Abstract
Inspection of kissing-bond defect in composite structure is a challenge for traditional nondestructive testing methods. In this paper, our work on NDT of C-sandwich radome for kissing-bond defect inspection was presented. A laser shearography system with vacuum loading device was used for inspection of a GFRP/NOMEX sandwich structure test panel with artificial defects. A serial of flat-bottom-holes whose diameter ranges from 25mm to 50mm was drilled in the back of the test panel to simulate the kissing-bond defects. Experimental results show that 25mm defect under skin could be found without difficulty by shearography. 38mm defect between the upper-layer honeycomb and middle skin could also be found. No indications found for the defects between middle skin and lower-layer honeycomb since the stiffness above the defects is very high, rigid motion covered the local deformation at detects. FEM was used for deformation calculation at the surface of defects with different vacuum loads. Calculation results agree with the experimental results.

Keywords: Shearography, Nondestructive testing, Kissing-bond defect, Honeycomb structure, Composite

1. Introduction
Bonded structures are being used extensively in aerospace companies to save on the costs and weight of composite aircraft. While flaws such as voids or disbands within a bondline could generally be found, the flaw of weakness in the bondline is a challenge for traditional NDT methods. "Kissing bonds" refer to flaws in bondline where surfaces are in intimate contact but with little bonding strength. Pierre Noël Marty studied the detectability of kissing bonds in adhesive joints and titanium diffusion bonds. They made quite a lot of efforts on producing test samples with controlled bonding strength. Although there has been some limited success in specific cases, no general NDT methods have proved successful for bondline assessment. The adhesive bond quality is a critical parameter that cannot yet be assessed by any NDT techniques. Several conventional methods are being optimized and developed for a better detection capability but up to day, no method can reliably and with a good reproducibility detect any weak adhesive bond, either on metal or composite substrate.

A C-sandwich radome was inspected in our lab with several NDT methods in manufacturing process. Ultrasonic through transmission (TTU) C-scan is the main method used for product quality control. But the flaw of weakness in adhesive bondline can’t be detected even with TTU C-scan method. After a period of service, it was found that disbond defects appeared under the surface of the radome. Failure analysis shows that weakness in bondline gradually becomes kissing-bond defects after some service time, then disbond defects generated finally. An in-service NDT technique that can find kissing-bond defects is needed. Pulse-echo ultrasonic inspection, thermography, Bondmaster, Woodpecker, etc. were tried on both the radome and test samples with artificial defects, but no satisfactory result obtained.
Laser shearography with vacuum loading may reveal the abnormal surface deformation above kissing bond defects in honeycomb structure. A test panel with simulated kissing-bond defects is made. Shearographic inspections are performed on the test panel. FEM analysis is also done on the displacement of the test panel. Displacement data from experiments and FEM analysis are compared to verify the reliability of the inspection.

2. Principles of laser shearography

Laser shearography or speckle pattern shearing interferometry is an optical measuring method similar to holographic interferometry. Laser holography can be regarded as the last generation NDT method of its kind, whose disadvantage of being too sensitive to environmental vibration limits its practical applications. Shearography uses coherent light to provide surface displacement information of the parts to be inspected. It has been widely used in production and development of composite structures in aerospace industry\(^5\)[6][7].

First used commercially in 1987 by Northrop Grumman on the B-2 bomber, laser shearography has emerged as an advanced, high-speed, high-performance technique that can detect changes in test part surface deformation. In the early time, optical interference fringe patterns should be interpreted by skilled person. Phase shifting technique was introduced into shearography in 1990s. The technique not only improves the inspection sensitivity by 10 to 100 times but also make a big progress in the image processing automation. Image interpretation becomes easier with the display of phase map image or 3D view of displacement field. Compare to ultrasonic C-scan techniques widely used in NDT of composite, shearography improves the inspection speed dramatically. It was reported that shearographic inspections of F-22 fighter components can be conducted at the rate of about 500 ft\(^2\)/hr, compared to about 10 ft\(^2\)/hr possible with ultrasonic C-scan testing\(^8\).

Advantages of shearography are the large area testing capabilities, non-contact properties, and relative insensitivity to environmental disturbances. Shearography is an active inspection method. It stresses the parts to be inspected with various ways such as vacuum, pressure, heating, vibration, etc. in order to generate abnormal surface displacement at location of defects.

Fig 1 is the typical configuration of laser shearography. Two points P1 and P2 at surface of part are imaged to the same point P1 at CCD camera by the optical shearing device. Here it is a Michelson interferometer. The angle of Tilt mirror control the shear distance and shear direction. Comparing images at two different loading states by digital image processing, system could generate optical interference fringes corresponding to the displacement of the observed surface. Move the phase shift mirror move back and forward several times at the same loading state and grab the images to realize phase shifting function. Phase maps show much better image quality than the fringe patterns. By integration of phase map, 3D-view of displacement provides the accurate and realistic images of defects.
Fig. 1 configuration of shearographic system and typical inspection images

The shearographic inspection system used in our experiments is LTI-5100. Vacuum loading device model is VG-100. It is a portable vacuum chamber with a glass window allowing outside laser illumination and observing by the shearing camera. Initial state images are grabbed at vacuum pressure of 20 inches water column (W.C.). Increase the vacuum pressure to a specific value, and grab the images as second state. Calculate the images grabbed at the two different deformation states, unwrapped phase images could be shown, 3D plot of out-of-surface displacement field could be displayed, too.

The working distance, the distance between the shear camera and the test panels, keep unchanged for all the experiments. It is 1.6m. Shear distance of 0.5 inch (12.7mm) is also keep the same for all the experiments. The size of field of view is about 150mm×150mm.

3. Test panel with artificial defects

To manufacture test panels with weakness in bondline, it is very hard to quantitatively control the bonding strength. It is almost impossible for honeycomb structure with Membrane. We only consider kissing-bond defects whose bonding strength is zero. From the point of view of mechanics, surface of the honeycomb structure panel will respond the same way for kissing-bond and disbond defects if the vacuum is the loading method. Air trapped in the honeycomb cell push the skin up when vacuum loading applied.

Teflon inserts are frequently used as artificial disbond defects in composite test panel for ultrasonic testing. But it is not a very good way to simulate disbond for shearography with vacuum loading. Sometimes honeycomb wall cut through the Teflon inserts and glue bonded the damaged area and made shearography hard to detect the inserts. So we decide to make it simple by drilling flat-bottom-holes (FBHs) from the other size to simulate kissing bond defects.

Fig. 2 show the C-sandwich honeycomb test panel we manufactured for experiments on inspection of kissing bond defects. It consists of 3 layers of GFRP skin and 2 layers of NOMEX honeycomb. Size of the panel is 700mm×540mm. Thickness of the upper and
lower skin was 1.5mm. Thickness of middle skin was 1.0mm. Height of the both honeycomb layers is 13mm.

9 FBHs are drilled from the back surface of the panel. Considering the possible locations of the kissing-bond defects, 3 different depths are controlled to simulate 3 different types of defects, as show in fig. 2b. For every type, 3 FBHs with different diameters (ϕ50mm, ϕ38mm and ϕ25mm) are drilled.

Type I: FBHs are drilled from lower skin to the upper-layer honeycomb, and leave the upper skin undamaged. Simulate the kissing bond defects between upper skin and upper-layer honeycomb.

Type II: FBHs are drilled from lower skin to middle skin, and leave the upper-layer honeycomb undamaged. Simulate the kissing bond defects between upper-layer honeycomb and middle skin.

Type III: FBHs are drilled from lower skin to lower-layer honeycomb, and leave middle skin undamaged. Simulate the kissing bond defects between lower-layer honeycomb and middle skin.

Fig.2 b) shows the vacuum chamber with a window on test panel.

4. Results and discussion

All the artificial defects (FBHs) are inspected from the upper side of the test panel. Vacuum loadings used are 10/15/20/30 inches W.C. Out-of-surface displacement above the defects are calculated by the software installed in the shearography system. FEM is used to calculate the theoretical out-of-surface displacement simultaneously and the results are compared with the experimental results.

4.1 Type I defects

Unwrapped phase image and 3D plot of type I ϕ50 defect obtained from shearographic testing is shown in fig.3. Vacuum loading used is 15 inches W.C. FEM gives the maximum
displacement at the centre of the defect is 5.8μm. Shearographic system give the maximum displacement is 5.3μm.

Fig. 3 Unwrapped phase image and 3D plot of type Φ 50mm defect

Change the vacuum loading from 10 inches W.C. to 30 inches W.C. we got the relationship between vacuum loading and the maximum out-of-surface displacement, as shown in table 1. Displacement comparison between experimental results and FEM calculation for Type I Φ50mm defect is displayed in fig. 4.

Table 1 Vacuum loading vs. Max. displacement of type Φ50mm defect

<table>
<thead>
<tr>
<th>Vacuum loading (inches W.C.)</th>
<th>FEM Calculation (μm)</th>
<th>Measured value (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.85</td>
<td>3.83</td>
</tr>
<tr>
<td>15</td>
<td>5.77</td>
<td>5.34</td>
</tr>
<tr>
<td>20</td>
<td>7.69</td>
<td>5.97</td>
</tr>
<tr>
<td>30</td>
<td>11.55</td>
<td>10.01</td>
</tr>
</tbody>
</table>

![Graph showing out of surface displacement vs. vacuum loading]
The fringe patterns and/or phase images of the defects obtained are in good image quality. Displacements form shearographic measurement agrees well with the FEM calculation. The results show that the shearographic system used can provide reliable displacement data.

Fig. 5 show the unwrapped phase image and 3D plot of Type I φ38mm defect at vacuum loading of 30 inches W.C. The experimental results show that our shearography system can inspect Type I φ38mm defect under vacuum loading from 10 to 30 W.C.

Fig. 6 shows Fig 6 Unwrapped phase image and 3D plot of type I φ25mm defect at vacuum loading of 15 inches W.C. Experimental results show that, for type I defect, even the smallest artificial defect in the panel can be detected by shearography system under loading of 10-30 inches W.C.

4.2 Type II defect

Type II defects locates deeper than type I. The structure above Type II defects is stronger. Compare with type I, less displacement will be observed at the same vacuum loading. Type II
defects will be harder to be inspected. Fig. 7 is unwrapped phase image and 3D plot of typell \( \phi 38 \)mm defect.

![Unwrapped phase image and 3D plot of typell \( \phi 38 \)mm defect](image)

The image obtained shows that typell \( \phi 25 \)mm defect could be detected, too. But the image becomes noisy. Inspection of type II defects is very attractive function, since the defects in middle skin can only be reliably inspected with TTU C-scan before. The results obtained here prove that shearography has the potential ability to inspect middle skin defects if size if the defect is big enough.

**4.3 Type III defect**

Compare with type II defects, the stiffness of structure above type III defects is even bigger. It is harder to stimulate deformation big enough to be inspected by shearography. Vacuum loading system has reached a maximum vacuum of 30 inches water column, but the shearographic system still can’t find the largest (\( \phi 50 \)) defect in the test panel.

Theoretically, increase the vacuum pressure may increase the inspection sensitivity. But general rigid deformation caused by air pressure under the vacuum chamber may disturb the fringe pattern of defects and make it hard to distinguish flaw area from sound area. Application of large vacuum chambers may get high sensitivity without rigid movement interference, but it is not convenient to use large vacuum chambers in service for large parts.

**4.4 About the sensitivity of shearography**

From the above experiments, it was obvious that the bigger the surface displacement is, the easier shearography could find the defect. For commercial available shearography system, phase shifting is a must-have function. Technical specification of displacement measurement sensitivity is always in the order of nanometers. Based on the experiments above, considering the rigid movement of the test panel and noise in image, 1μm of abnormal out-of-plane displacement can be used as a rough threshold for shearography inspection under vacuum hood loading. Prediction of possible maximum deformation at the surface of defect could help to make decision on choice of the shearography method.

**5. Conclusions**
1) A C-sandwich honeycomb structure test panel with artificial defects was inspected by using laser shearographic system with vacuum loading. The out-of-surface displacements obtained from shearographic measurement agree with FEM calculation. The results show that laser shearography is an effective method to inspect kissing-bond defect in honeycomb structure.

2) The shearography system used in the experiments give satisfactory results when the out-of-surface displacement at the centre of the defect is bigger than 1μm.

3) For the test panel used in our experiments, size as small as φ25mm defect under the outer skin can be found without difficulty; size bigger than φ38mm defect between upper-layer honeycomb and middle skin can detected effectively. It proves shearography has the potential capability to detect defects at septum of honeycomb structure.

References