FULL FIELD STRAIN CHARACTERISTICS OF COMPOSITE LAMINATE WITH IMPACT DAMAGE UNDER IN-PLANE LOAD

Z. Yu*, Bataxi1, H. Wang1
1 School of Aeronautic and Astronautic, Shanghai Jiao Tong University, Shanghai, China
* Corresponding author (yuzf@sjtu.edu.cn)

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1 Introduction

The full-field measurement becomes more and more popular in the structural experiment [1]. The composite laminate is susceptible to transverse impact which may dramatically reduce the structural strength. The impact usually produces the local damage, and full field measurement can show the local response variation. The delamination in composite laminate subjected to bending load can be detection with deflectometry technique [2,3]. Kim, etc.[4] used this technique to measure the local stiffness reduction. The delamination is much easier to detect if it is bulged under the external load. Maranon etc.[5] proposed a method for subsurface delamination identification. In a vacuum chamber, the out of plane displacement due to the negative pressure was measured with the digital speckle pattern interferometry. The identification procedure consists steps of edge detection, delamination estimation and characterization (i.e. the location size, orientation and depth). Before the failure of the laminate with delamination subjected to compressive load, the delamination buckling may occur in the delaminated region[6], which also brings the variation in the strain field.

In this paper, the numerical study is firstly carried out on the surface strain characteristics of laminate with impact damage, including fiber breakage and delamination. Then the strain fields of the composite specimen subjected to the in-plane tensile and compressive are measured using digital image correlation (DIC) technique. The influence of DIC parameter on the damage detection is discussed.

2 Numerical Study

2.1 Finite Element Model

The laminate is modeled with continuum shell element (SC8R) using ABAQUS software(Fig.1), with a dimension of 60mm×60mm×1mm and a ply setup of [0/45/-45/90]s. The material properties are listed in Tab.1. A set of cohesive element of 0 thickness were created to simulate the interlaminar force and the material properties are listed in Tab.2. It is assumed that the delamination will not grow in the loading. In the delamination region, no cohesive element is created, and the General Contact is added to avoid the penetration of layers thus produce the correct buckling direction. The impactor is modeled with a rigid sphere.

Fig.1 FE model of the laminate

<table>
<thead>
<tr>
<th>Table 1 Material properties</th>
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<tr>
<td>$E_{11}$/GPa</td>
</tr>
<tr>
<td>134</td>
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Table 2 Cohesive properties

<table>
<thead>
<tr>
<th>$K_n$</th>
<th>$K_s$</th>
<th>$K_t$</th>
<th>$T$</th>
<th>$S$</th>
<th>$G_{Ic}$</th>
<th>$G_{IIc}$</th>
<th>$G_{IIIc}$</th>
<th>$\eta$</th>
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</thead>
<tbody>
<tr>
<td>$1 \times 10^3$</td>
<td>10</td>
<td>61</td>
<td>68</td>
<td>0.227</td>
<td>1.105</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Damage Simulation

A forced displacement in x direction is exerted in one edge of the laminate, and the opposite edge is fixed in x, y, and z direction, and the other two edges are fixed in z direction.

![Delamination](image1.png)

(a) Delamination

![Fiber damage](image2.png)

(b) Fiber damage

Fig.2 Damage when indentation equals 3mm

The quasi-static indentation procedure is used to simulate the impact damage (Fig.2) instead of using dynamic simulation. These damage are identical to those obtained by impact simulation. The damage data must be transmitted to the simulation of response under the static in-plane load. The restart technique is adopted to simulate responses of the laminate subjected to in-plane tensile, compressive and shear load.

3 Strain Characteristics

3.1 Static Strain

The surface strain are obtained, with tension, compression and shear, respectively. Under the tensile load, the heigher strain in the damage region are very clear (Fig.3.a), which is mainly caused by the fiber breakage and matrix crack. However, under the compressive load, the magnitude of strain in the damage region is lower than those of other region (Fig.3.b). For the shear load, the magnitude of strain in the damage region is higher (Fig.3.c). The strain near to the boundary is distinct from that of the rest, but the value is close to zero.

In practice, this kind of abnormal data must be qualified with a mathematic tool. The standard deviation (STD) of strain is employed to evaluate the abnormal strain. Acrossing the damage region, the strain value in a row (x direction) and in a column (y direction) are extracted, respectively. And then the STD of these two set of strain value for a tensile case are calculated (Fig.4). By Fig.4, the STD of damaged region is obviously higher than those of other regions, which is helpful for damage identification. Furthermore, the coefficient of variance of a set of strain is more reasonable, for it is dimensionless. The variance is related to STD, so it will not be discussed any more.

With the STD of a row and a column of strain value, the damage location can be determined. Drawing a rectangle with a width and a height according the ‘length’ of the heigher STD shown in
Fig. 4, the damage area is obtained (Fig. 5), which consistent with the fiber damage shown in Fig. 2.b.

Fig. 3 Strain field under in-plane load

(a) Under tensile load

(b) Under compressive load

(c) Under shear load

Fig. 4 The standard deviation of strain data

(a) In x direction

(b) In y direction

Fig. 5 The damage area obtained with strain STD
3.2 Strain of Delamination Buckling

In Fig.3.b, the magnitude of strain in damage region is lower under the compressive load, for the relative lower load is carried by this part region. But if the compressive load is higher enough, the delamination buckling may occur. In this case, the strain magnitude of damage region will become much higher.

There are three types of delamination buckling mode[6], global, mixture and local, which can be simulated with finite element model (Fig.6).

In the case of mixture buckling mode, the strain singularity of the damaged region may be also covered by the high strain due to the buckle of the rest part. If the local buckling mode occurs, the strain singularity is easy to observe due to the bulge of the delaminated region (Fig.9.a). By the Laplacian-based edge detection[5], the size of delamination is easy to get.

For some delaminations, if they are located in the center, the mixture buckling may be occur, therefore the damage can not be observed. But if it is located near to the boundary of the plate, the local buckling may also be shown due to the strain singularity (Fig.9.b).

![Fig. 6 Delamination buckling modes](image)

![Fig. 7 Strain field of the intact laminate](image)

![Fig. 8 Strain field of the laminate with small size damage](image)
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4 Experimentation
4.1 Experimentation Setup

The strain field of composite specimens with damage are measured. Firstly, the dropping weight impact test is carried out to produce the damage in the composite. A single lens reflex camera is employed to catch the speckle photography of the composite specimen in the loading procedure (Fig.10). The digital image correlation (DIC) technique is used to obtain the strain field.

The grid is created in the image for displacement measurement (Fig.11). Each node covers an area of 25pixel×25pixel. The displacement data of every 10 nodes are used to calculate the strain. The precision of strain measurement increases with the node number, yet the sensitivity to the damage decreases with it. This effect is shown as Fig.12. Under the tensile load, the strain field of the specimen shows the crack in the impact surface. In the strain field formed by the strain data obtained with 50 nodes, the crack detail are blurred (Fig.12.c).

Under the compressive load, the crack is not easy to see, but on the opposite surface of impact the strain variation is observed (Fig.13). Also, in a high compressive load, the delamination buckling may occur. The strain field of local buckling is shown in Fig.14, where the boundary of the bulge of the delaminated region is figured out by the strain field.

If the global buckling occurs, the strain field cannot show the damage and its boundary clearly (Fig.15). There strain in the middle of the plate are large, and for most case it is hard to judge what has caused the large strain, the global buckling or the degradation of the stiffness. There are some problems, such as the principle and the process, of delamination buckling needed to investigate.

Fig. 9 Strain field for local delamination buckling
(a) Damage in the center
(b) Damage in the corner

Fig.10 Experiment setup
Fig. 11 Grid in the image

(a) 10 nodes

(b) 25 nodes

(c) 50 nodes

Fig. 12 Strain field in the front surface under tension obtained with different grid node number
Fig. 13 Strain field in the back surface under compression

Fig. 14 Strain field of delamination buckling

Fig. 15 Global buckling in the front surface of laminate with impact damage

3 Conclusion

With the strain field, the impact damage in the composite laminate with impact damage under tensile, compressive and shear load can be shown by the higher of lower strain in the damaged region. With the standard deviation of the strain data, the damage can be detection and its size can be obtained.

The strain field in delamination buckling can be adopted to identify the damage. In the simulation, only the local buckling mode shows the delamination.

The DIC technique can used to detect the singularity of the strain field. The fiber breakage and the matrix crack can be detected, but the sensitivity is related to DIC parameters which should be taken notice in practice. The delamination buckling is easy to observe with the DIC strain field, and the mechanism of delamination buckling should be investigated to improve the damage identification.

References

[1] M. Grediac “The use of full-field measurement methods in composite material characterization:


