Experimental study on the stitching reinforcement of composite laminates with a circular hole

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Abstract

Experimental study is carried out on the stitching reinforcement of composite laminates containing a circular hole. First, the tensile strength and stiffness are measured, and their dependence on stitching parameters such as stitching needle span, row spacing, edge distance and stitching type are analyzed. Next, the strain distribution and concentration are investigated analytically and experimentally for different stitching parameters, external load and edge location of the hole. It is shown that the results of stitching reinforcement are quite different for composite laminates with a circular hole, which could provide proper stitching parameters for designers.

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1. Introduction

Advanced composite panels with holes are widely used in aerospace structural components. In such structures, stress concentration around a hole normally causes failures. As a typical example, the internal damage induced by stress concentration can not be found at the early stage of loading and may propagate as the load increases. On the other hand, the type and extent of the damage significantly affect the strength, service life and the performance of the composite structures. Hence, the study on the stress concentration around a hole in composite laminates is of great practical importance, and has received considerable attention.

Eiblmeyer [1] investigated the influence of cut-out diameter and reinforcement type on the buckling stability of CFRP panels. For this purpose, several finite element models were suggested for different loadings, cut-out sizes and reinforcement rings. Practical tests were also conducted to validate their numerical results.

Mahdi et al. [2,3] focused on the mechanical performance of repaired stiffened panels under compression respectively via the experimental study and the finite element analysis. A pristine panel was compared with the panels containing a through hole, as well as with the repaired panels. The modeling of failure, stiffness and strains were studied. It was shown that the significant decreases in strength caused by the damage were almost fully recovered by the repair scheme used.

Gliesche [4,5] developed the Tailored Fiber Placement Technology (TFP), and applied it to manufacturing a stress-field aligned local reinforcement on an “open-hole” tensile plate. The TFP technology could relieve the stress concentration in a notched composite. Using the finite element analysis the stresses in the open-hole plate were determined under unidirectional tensile loading. The strain distributions were investigated for different loading conditions by the optical deformation measurement method.

The reinforcement of polymer matrix composites by through-the-thickness stitching is a promising technique for raising the damage tolerance of laminar structures. In 1990s, Mai et al. [6–10] published series of work to assess the potential applications of stitched laminates. Later,
Mouritz and Cox [11] proposed an approach to evaluate the properties of the stitched laminates. These studies showed that the load-carrying capacity of the laminates can be improved through a proper stitching reinforcement.

The objective of this paper is to study the stitching reinforcement in composite laminates with a circular hole. The effects of the stitching parameters such as stitching needle span (the stitch-to-stitch spacing along the hoop direction around a hole), row spacing (the row-to-row spacing along the radial direction), edge distance (the minimum radial distance between the hole edge and the stitch line) are taken into account. The strains are measured for different stitching parameters, external load and edge location of the hole, on which the corresponding strain concentration factor and the failure strength for this kind of composite laminates are studied.

2. Basic ideas

Assume that \( \sigma^\infty \) is the stress applied at infinity. Thus, the stress distributions at the hole edge have a maximum value \( \sigma_{\text{max}} \). For the purpose of description, the stress concentration factor (SCF), say \( K_e \), is used as usual and defined as

\[
K_e = \frac{\sigma_{\text{max}}}{\sigma^\infty}
\]  
(1)

The composite laminate is composed of a number of layers with different material properties, so the stress distributions around the hole are different for each layer. Considering the fact that all of the adjacent layers are well bonded together, the interlaminar stresses will be ignored and the strains of the individual layers are assumed to vary with the laminate. As the common practice, the SCF around holes in multilayered plates can be expressed as the weighted average of the SCFs for all layers, that is

\[
K_e = \frac{\sum_{i=1}^{m} N_i K_{i}}{N}
\]  
(2)

where \( N \) is the gross number of the layers, \( m \) is the number of plies with different fiber lay-up directions, \( N_i \) is the repeated layer number of the \( i \)th ply, and \( K_i \) is the SCF in the \( i \)th ply.

The SCF for each layer with a central hole was given by [12] as

\[
K_{i}^{\infty} = 1 + \sqrt{2\left(\frac{E_y}{E_x} - v_{yx} + \frac{E_x}{2G_{yx}}\right)}
\]  
(3)

\[
\frac{K_{i}^{\infty}}{K_{i}} = \frac{3(1 - d/W)}{2 + (1 - d/W)} + \frac{1}{2} \left(\frac{d}{W M}\right)^6 \left(K_{i}^{\infty} - 3\right) \times \left[1 - \left(\frac{d}{W M}\right)^2\right]
\]  
(4)

where \( K_{i} \) and \( K_{i}^{\infty} \) denote the SCFs of the finite plate and the corresponding infinite plate, respectively, at the hole edge whose normal is 90° away from the applied load direction. \( E_x \) and \( E_y \) are Young’s moduli respectively in \( x \) and \( y \) direction, and \( G_{yx} \) and \( v_{yx} \) are respectively the shear modulus and Poisson’s ratio in \( x-y \) plane. \( M \), the magnification factor, is a function of \( d/W \) (ratio of hole diameter to plate width) and can be expressed by

\[
M^2 = \sqrt{1 - \frac{\left[\frac{3(1 - d/W)}{2 + (1 - d/W)} - 1\right]}{2(d/W)^2}}
\]  
(5)

It is obvious that \( K_e \) (SCF) will be determined from Eq. (2) if \( K_{i} \) is known. However, the solution above mentioned for the stress concentration around a hole in the multilayered plate is not exact at the hole boundary. In the free edge region of the hole, shear stresses exist between various layers of a laminate. In addition, use of the correction factor for the finiteness of plate width may cause some error. So, there is room for Eq. (2) still to be improved. The same analysis can be performed for the strain instead around a hole. From the maximum strain value \( \varepsilon_{\text{max}} \) at the hole edge and the strain \( \varepsilon^{\infty} \) at infinity, the strain concentration factor \( K_e \) can be defined as

\[
K_e = \frac{\varepsilon_{\text{max}}}{\varepsilon^{\infty}}
\]  
(6)

The strains can be directly observed in specimens. Theoretically, the deformation in the local region of the hole is governed by the local stresses at the hole edge, so the stress concentration factor \( K_e \) and strain concentration factor \( K_e \) are correlated. That is to say, once the strain concentration at the hole edge is measured, the level of the stress concentration at the hole edge will be determined. Thus, this problem can be more exactly resolved by efficiently measuring \( K_e \) around the hole with experimental devices.

3. Experimental consideration

In order to study the effect of stitching parameters such as needle span, row space, edge distance, stitching type (i.e. single stitching or double stitching), the specimens are divided into five types, i.e. three types of single stitching reinforcement marked respectively by Single-1, Single-2 and Single-3, and two types of double stitching reinforcement marked respectively by Double-1 and Double-2. In the specimens, the stitching yarns are made of the Kevlar-49 (1600 denier) and stitched near the hole by use of the improved lockstitch [13]. In Table 1 are shown details of the stitching parameters.

The laminate with a circular hole is made of T300/Epox. The diameter of the circular hole is 60 mm. The fiber lay-up in the laminate is \([45/-45/0/90/0/90/-45/45]_{2s}\). The reinforced slices, which are made of LY12CZ, one kind of aluminium alloy, are separately bonded to the two ends of every specimen. Strain gauges (25–40) were bonded to various locations along the hole edge crosswise, and connected with a multipass strainometer. In Fig. 1 are shown the geometry and dimension of specimens.

The two ends of specimens were separately linked up with the tailored fixture and installed in the jaw of the
testing machine. The design and dimension of the fixture are shown in Fig. 2. The tensile experiments are carried out using a servo hydraulic material test system (MTS 880-10).

4. Results and discussion

The failure strength and strain of the specimens are defined as the maximum value of the longitudinal stress and strain at 0° point around the hole on the stress–strain curve. Tables 2 and 3 show respectively the failure strength of specimens and the failure strain of the hole edge for different stitching parameters.

A regular tensile stress-field is seen at infinity far away from the hole edge and from the location where the clamped boundary condition is prescribed. The curve of stress versus strain at infinity is plotted in Fig. 3, whereas the curve of stress versus strain at the hole edge where the cross-section is minimum is depicted in Fig. 4.

It is seen from Figs. 3 and 4 and Table 2 that the stiffness and the failure strength of the composite laminate with a hole increases because of stitching reinforcement at the

| Table 1 | Stitching parameters of stitching reinforcement on the hole |
|---|---|---|---|---|---|---|
| Stitching parameters | Single-1 | Single-2 | Single-3 | Double-1 | Double-2 |
| Needle span/mm | 3 | 3 | 5 | 3 | 3 |
| Row spacing/mm | 0 | 0 | 0 | 5 | 3 |
| Edge distance/mm | 3 | 5 | 3 | 3 | 3 |

| Fig. 2. Design and dimension of the fixture. |

| Fig. 1. Geometry and dimension of specimens. |

| Table 2 | Failure strength of specimens/MPa |
|---|---|---|---|---|---|
| Number | Unstitching | Single-1 | Single-2 | Single-3 | Double-1 | Double-2 |
| 1 | 204.76 | 201.19 | 240.24 | 232.86 | 241.67 | 238.10 |
| 2 | 223.81 | 251.19 | 239.52 | 214.29 | 258.33 | 226.19 |
| 3 | 182.86 | 223.10 | 220.24 | 220.24 | 233.33 | 203.57 |
| 4 | – | 195.24 | 240.05 | – | 204.29 | 214.29 |
| 5 | – | 209.52 | 209.45 | – | 226.19 | 216.19 |
| Average value | 203.81 | 216.05 | 229.90 | 222.46 | 232.76 | 219.67 |

| Table 3 | Failure strain of hole edge/μ |
|---|---|---|---|---|---|
| Number | Unstitching | Single-1 | Single-2 | Single-3 | Double-1 | Double-2 |
| 1 | 8204 | 8629 | 7230 | 8195 | 9027 | 8139 |
| 2 | 8474 | 8328 | 8059 | 8098 | 7295 | 10310 |
| 3 | 7143 | 8539 | 8506 | 7884 | 9706 | 8605 |
| 4 | – | 8619 | 9374 | – | 8874 | 10405 |
| 5 | – | 10368 | 8634 | – | 8519 | 8499 |
| Average value | 7940 | 8896 | 8361 | 8059 | 8684 | 9192 |
When reinforced by stitching at the hole edge, the fiber volume fraction is added in thickness, and the loads can be effectively transferred between the plies in the local reinforced region. This mechanism improves the load capacity.

Besides, attention must be paid to the re-distribution of the stresses in the laminate due to the stitching reinforcement at the hole edge, especially to the stress concentration and strain concentration newly generated by the closing of the stitching lines. From Table 3, it is seen that, reinforced by stitching, the maximum strain at the hole edge becomes larger, and hence the strain concentration at the hole edge is increased rather than decreased in this circumstance. This implies that the so-called notch strengthening may risk a sudden failure.

Fig. 5 shows the strain concentration factor $K_\epsilon$ with the distance from the hole edge (along the x axis) at the minimum cross-section around the hole. From Fig. 5, it is interesting that the distance of a radius of the hole. For the strain declination, the scope is roughly the same for both stitching and unstitching, but the level is different.

Fig. 6 depicts the variation of $K_\epsilon$ with load respectively at 0° point and at 90° point around the hole. From Fig. 6(b), we see that $K_\epsilon$ at 90° point are strongly dependent on the load. However, see Fig. 6(a), it is interesting that the
strain concentration factor $K_e$ at 0° point does not vary with the load for the given specimen (i.e. fixing the stitching parameters). $K_e$ for unstitching is about 3.3 and increases after stitching. For the case of the double stitching reinforcement, the maximum strain concentration is increased by 88% around as compared with that of the single stitching reinforcement. Considering the fact that the fiber volume fraction of the double stitching at the local regions is much higher than that of the single stitching, the local strengthening effect becomes more prominent after the double stitching reinforcement.

By comparing Fig. 6a and b, we also see that $K_e$ at 90° point is much larger than at 0° point. The reasons are two-folded. On one hand, the vertical and horizontal load affects each other due to the effect of the Poisson’s ratio at the local regions, where the material bore shrinks freely. This mechanism causes the compression deformation to quite a large extent. On the other hand, with the material shrinking freely, the vertical and horizontal deformations are no longer linearly dependent on the load after a critical value. According to the definition, $K_e$ does not remain a constant under this circumstance, but changes with the applied load and the local deformation.

5. Conclusions

From the current work, we conclude that the stiffness and the failure strength of the composite laminate are increased after stitching reinforcement. There exists a notch strengthening effect, which implies that the maximum strain at the hole edge becomes higher. Comparing the stitching reinforcement with unstitching, the scope of strain declination is roughly the same, but the declination level is obviously increased. The strain concentration factor $K_e$ at 90° point around the hole varies with load, whereas $K_e$ at 0° point keep the relevant constant for a given specimen. For anisotropic laminates $K_e$ is various at different point around the hole, unlike the isotropic plates. Combining the results in all respects, the Single-2 and the Double-1 are the better choices for the composite laminates when reinforced by stitching on the hole.

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