# NUMERICAL ANALYSIS ON BEARING BEHAVIOR OF COMPOSITE BEAM WITH OPEN-HOLE

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## ABSTRACT

This study aims to investigate the numerical analysis of bearing behaviour on C section beam with different types of open-hole on web. The beam is composed of five composite parts, four metal parts and numbers of bolts. Four composite beams, with circle hole, rectangular hole, eccentric rectangular hole and strengthen rectangular hole on the web, are analysed respectively. The beams were subjected to two types of loads, including the maximum shear load and the maximum bending-shear ratio load, which were selected from the design load on the front-spar of wingbox for an experimental demand. A linear three-dimensional finite element model in HYPERWORKS platform was developed. To understand the bearing behaviour, the stress/strain of the structure and the maximum stress around the holes were analysed. Verification calculations of the beam web were performed with the margin equations. It was found that the maximum shear strain of composite parts appear right at the opening edge under both two loads. The beam with circle opening has the minimum strain and stress value while the stress concentration positions are various with the change of hole forms.

## 1 INTRODUCTION

Carbon fibre reinforced epoxy laminate has been wildly applied in the field of aero vehicle structural design, due to its several well-established advantages, specific stiffness and strength over metallic materials. Meanwhile, structural discontinuities such as open holes or cutouts are inevitable in composite structures for some engineer purposes, like connection, joint, assembly, etc. The presence of holes interrupted the continuous distributions of stress and strain within the structure and will create stress or strain concentrations around the holes, hence will reduce the mechanical properties [1]. Therefore, the mechanical behaviours of structure with open holes take a serious consideration. Kumar and Singh [2] undertook an analytical study on the stability and failure of a composite laminate with various shape of cutouts in central, include circle, square, diamond, elliptical openings under combined in-plane loads. Furthermore, some studies on finite element analysis of composite structure with hole were also taken. Loughalam et al. [3] carried out an analysis of stress concentration in plates with rectangular openings.

The aim of this paper is to gain a numerical understanding of the influence of the open-hole configuration on bearing behaviour of the composite C section beam. The sample structure and analyse methods are identified firstly. Afterwards, The effects of hole shape (circle hole, rectangular hole, eccentric rectangular hole and strengthen rectangular hole), and lode types (maximum shear load and maximum bending-shear ratio load) are explored in detail. Finally, the stress/strain of the structure are analysed to further understanding the stability of the structure as well as the effect of hole shape.

## 2 SAMPLE PRESENTATION

Brief details of the component of C section composite beam with open-holes are given here. Thbeam is composed of composite parts, metal parts and numbers of bolts. As shown in Fig.1, One C section composite beam bolted with two composite skin plates on the outside surfaces of the top&bottom C section flanges, two other composite plates are bolted on the inside surfaces of the skin plates. Four aluminium alloy plate are fixed symmetrically about the open-hole, which are take the place of the rib in wingbox.

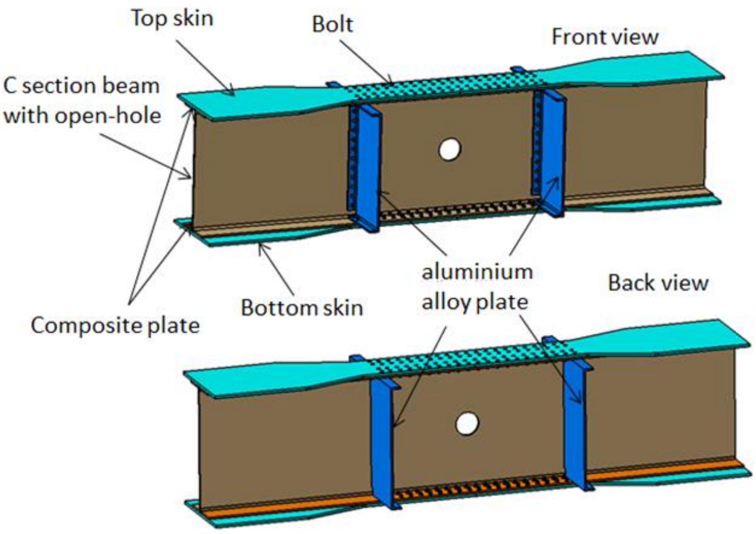



Figure 1: composite beam with circular hole.

Four composite beams were analysed in this study with circle hole, rectangular hole, eccentric rectangular hole and rectangular hole with a strengthen composite plate respectively. The four open-hole types were chosen in accordance with the need of wingbox spar. The open-hole is positioned in the centre of the beam web, except the eccentric rectangular hole has an upward shift.

A linear three-dimensional finite element models in HYPERWORKS platform was developed. Fig.2 exemplifies the numerical model of the composite beam with circle hole. In the FE model, the shell element (QUAD4) was used to model composite and metal parts. By considering the computational cost and basic refinement around the hole edge, the mesh size was set approximately uniformly, about 3mm around the holes and about 8 mm in the non-critical regions. The fibre direction (0 °) was defined along the beam length direction. On the other hand, the fastener was modelled using the CBUSH elements. A sufficient number of elements, about $1.1*10^5$ elements were included in this analyse.

Besides, the loading procedure, boundary conditions, material properties and sample geometry in the FE model were set to simulate the experimental.

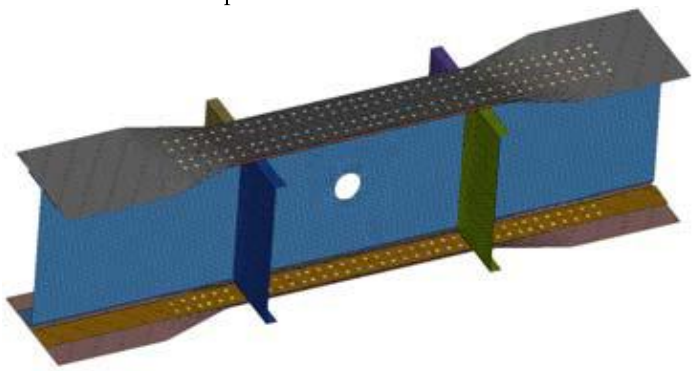


Figure 2: beam model with circle hole.

## 3 MATERIALS AND METHODS

A common aerospace grade/T800 carbon fiber/epoxy prepreg was chosen for this analysis. The average tensile strength and Young’s modulus, determined from the room temperature and dry tests according to ASTM D3039, were 2920 MPa and 164.5 GPa, respectively. The elastic material constants of Al used as false ribs were given in Table 1.

Table 1 material properties of aluminum alloy

| ***E*** (MPa) | ***G*** (MPa) | $\nu$ | Thermal expansion coefficient($10^{-6}$/℃) |
|---|---|---|---|
| 71016 | 26890 | 0.33 | 23 |

In order to study the bearing behavior of the open hole composite beam, the beams were design to withstand all serious situation may appeared during the service period. Two loads were selected from the design load on front-spar of wingbox for an experimental demand, including the maximum shear load and the maximum bending-shear ratio load.

The maximum strain criterion was used for the strength verification of composite.The margin equation (1) can be given as:

$$\mathrm{M.S.} = \mathrm{Min}\left\{\frac{[\varepsilon_T]}{\varepsilon_T} - 1, \frac{[\varepsilon_C]}{\varepsilon_C} - 1, \frac{[\gamma]}{\gamma} - 1\right\} \tag{1}$$

Where $[\varepsilon_T]$ is tensile failure strain, $\varepsilon_T$ is maximum tensile strain, $[\varepsilon_C]$ is compression failure strain, $\varepsilon_C$ is maximum compression strain, $[\gamma]$ is shear failure strain, $\gamma$ is maximum shear strain. Here the unit for strain is με.

An independent equation (2) was used for the strength verification of open-hole. As shown in Fig.3, the tensile stress and compression stress of the 0 degree ply on the tangential direction at a characteristic distance $d_0$ to the hole was chosen to verify the margin [4].

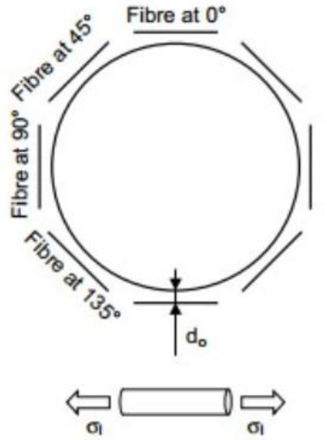



Figure 3: Sketch map of the verification method around the hole.

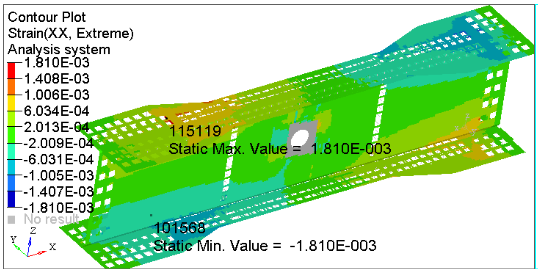
$$\mathrm{M.S.} = \mathrm{Min}\left\{\frac{[S_T]}{S_T^{d_0}} - 1, \frac{[S_C]}{S_C^{d_0}} - 1\right\} \tag{2}$$

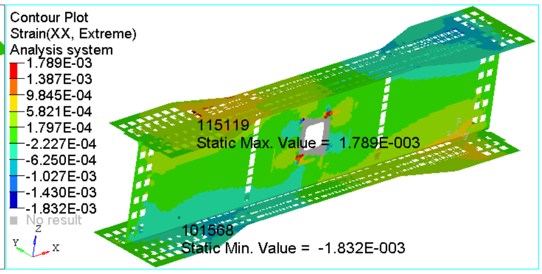
Where $d_0$ denote the characteristic distance to the hole, $d_0$ has independent value for circular hole and rectangular hole respectively, $[S_T]$ is 0°directional tensile failure stress. $S_T^{d_0}$ is tensile stress of the 0 degree ply on the tangential direction at a characteristic distance $d_0$ to the hole, $[S_C]$ is 0°directional compression failure stress. $S_C^{d_0}$ is compression stress of the 0 degree ply on the tangential direction at a characteristic distance $d_0$ to the hole. Here the unit for stress is Mpa.

## 4 RESULTS AND DISCUSSION

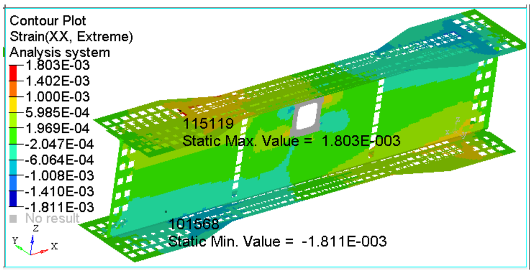
### 4.1 Strain of structure

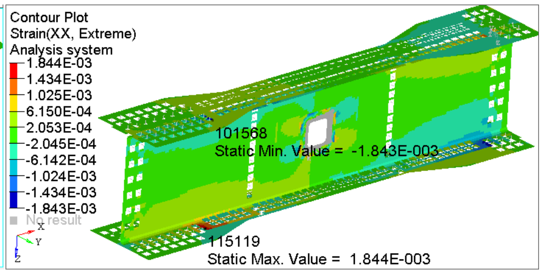
As shown in Fig.4 and Fig.5, for the strain fields in X (the fibre direction) direction of the beam, the maximum tension and compression strain value appear at the similar position of the beam: under the maximum shear load (Fig.3) and the maximum bending-shear ratio load (Fig.4).





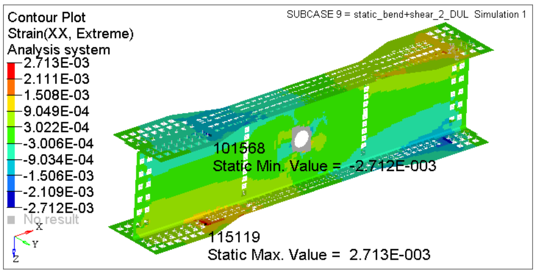

(a) (b)

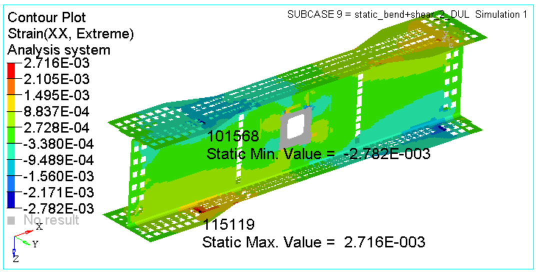




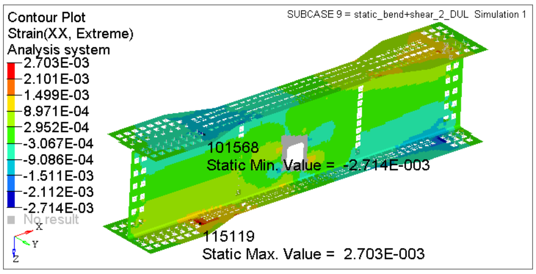

(b) (d)

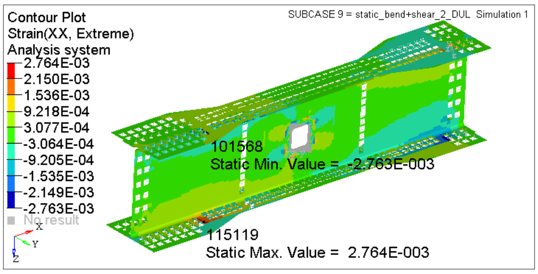
Figure 4: The strain fields in X (the fibre direction) direction of the beam under the maximum shear load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.






(a) (b)






(c) (d)

Figure 5: The strain fields in X (the fibre direction) direction of the beam under the maximum bending-shear ratio load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

As shown in Fig.6 and Fig.7, the strain fields in Y (perpendicular to the fibre direction) direction of the beam, the maximum tension and compression strain value also appear at the similar position of the beam: under the maximum shear load (Fig.5) and the maximum bending-shear ratio load (Fig.6).

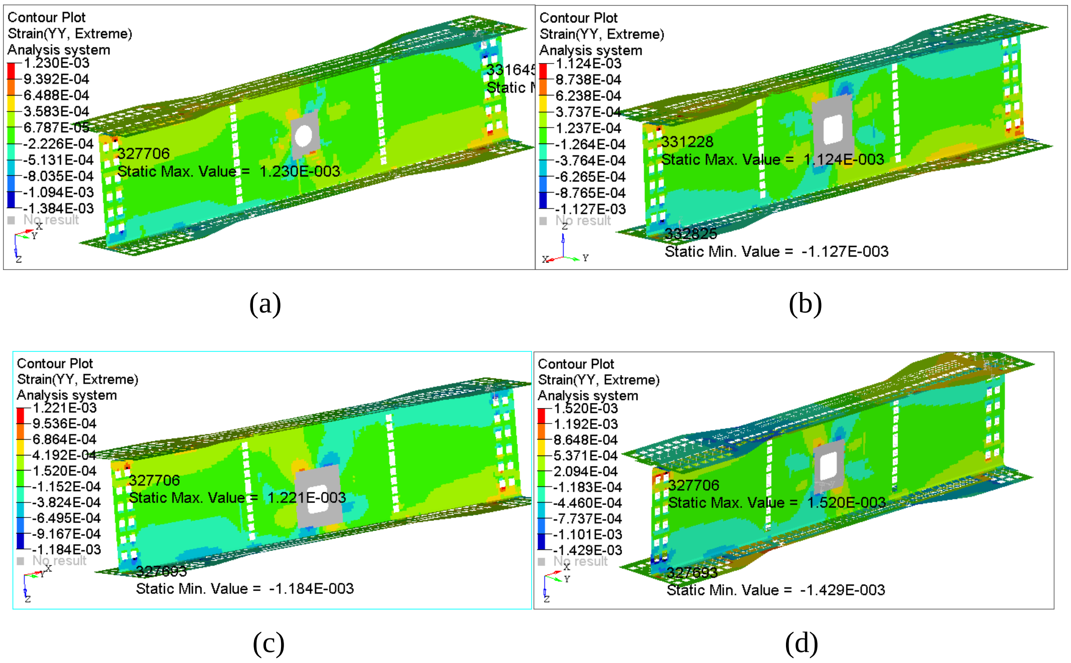



Figure 6: The strain fields in Y (the fibre direction) direction of the beam under the maximum shear load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

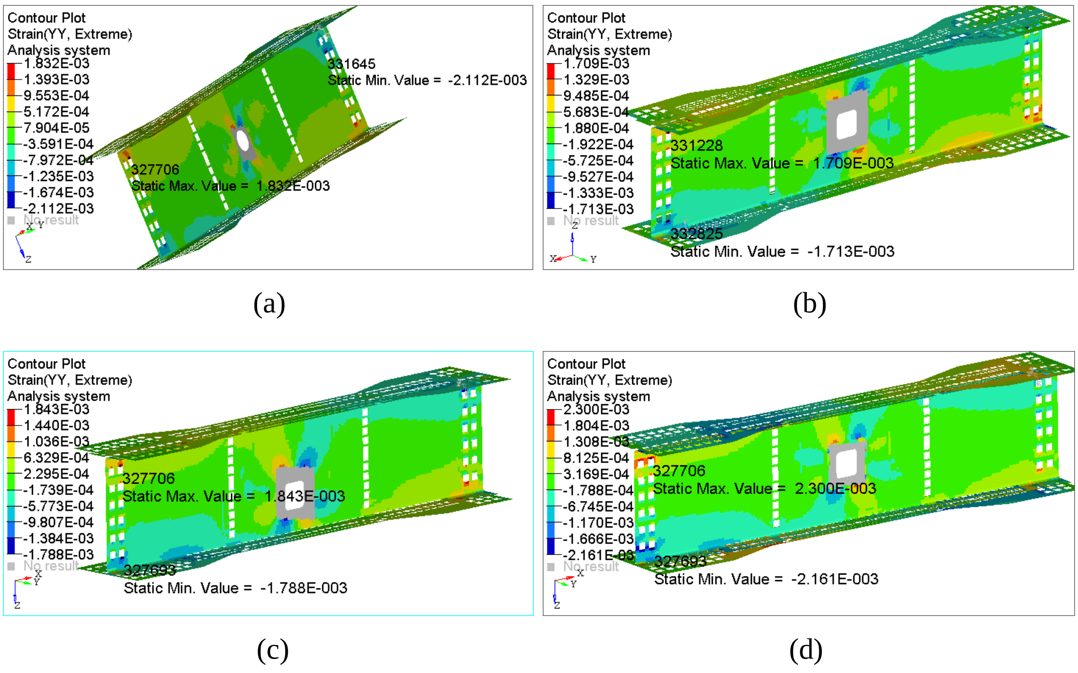



Figure 7: The strain fields in Y (the fibre direction) direction of the beam under the maximum bending-shear ratio load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

Figure 8 and Figure 9 present the shear strain fields of the beam under the maximum shear load and the maximum bending-shear ratio load, respectively. It is easily seen that the maximum shear stress of composite parts appear right around the hole edge and the maximum values are approach. In addition, the top and bottom symmetry and bilateral symmetry appear very good as well.

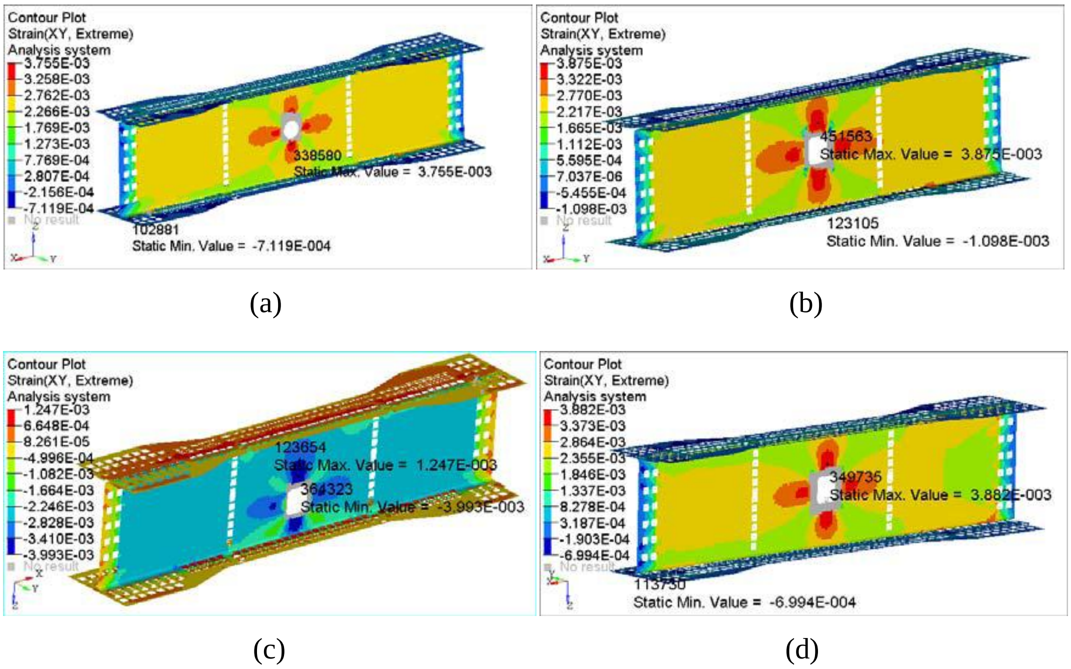



Figure 8: The shear strain fields around different openings under the maximum shear load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

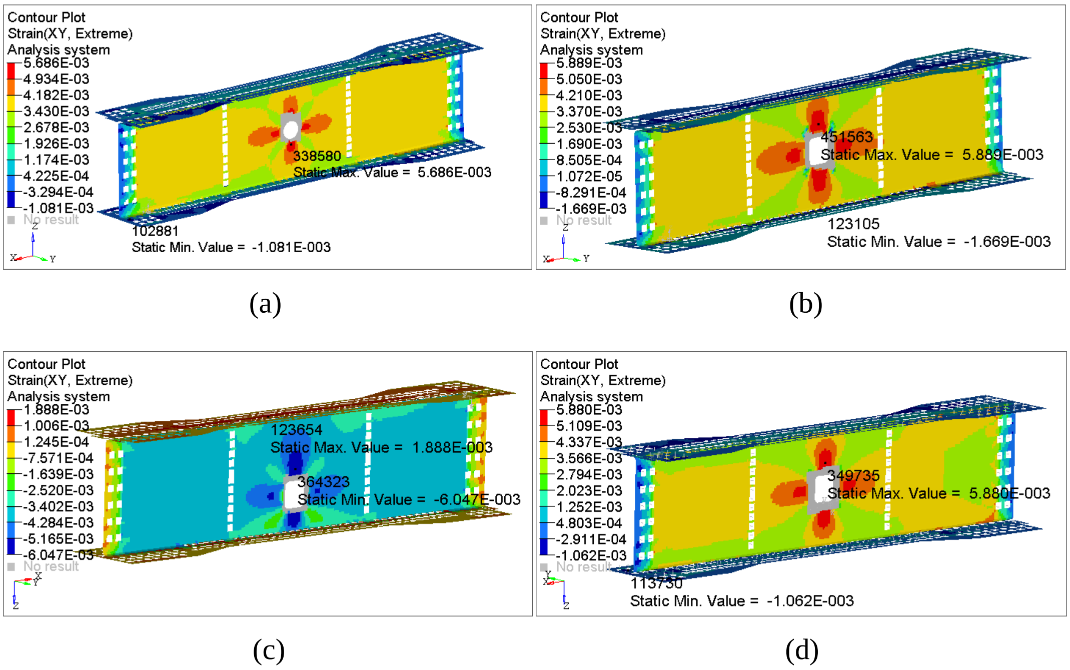



Figure 9:The shear strain fields around different openings under the maximum bending-shear ratio load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

Table 2 Comparison of the maximum tension strain, compression strain, shear strain value under the maximum shear load.

| | | Circle hole | Rectangular hole | Eccentric rectangular hole | Strengthen rectangular hole |
|---|---|---|---|---|---|
| Tension strain(X) | [με] | 1810 | 1789 | 1803 | 1844 |
| Compression strain(X) | [με] | 1810 | 1832 | 1811 | 1843 |
| Tension strain(Y) | [με] | 1230 | 1124 | 1121 | 1520 |
| Compression strain(Y) | [με] | 1384 | 1127 | 1184 | 1429 |
| Shear strain | [με] | 3755 | 3875 | 3993 | 3882 |

Table 3 Comparison of the maximum tension strain, compression strain, shear strain value under the maximum bending-shear ratio load.

| | | Circle hole | Rectangular hole | Eccentric rectangular hole | Strengthen rectangular hole |
|---|---|---|---|---|---|
| Tension strain(X) | [με] | 2712 | 2716 | 2703 | 2763 |
| Compression strain(X) | [με] | 2713 | 2782 | 2714 | 2764 |
| Tension strain(Y) | [με] | 1832 | 1709 | 1843 | 2300 |
| Compression strain(Y) | [με] | 2112 | 1713 | 1788 | 2161 |
| Shear strain | [με] | 5686 | 5889 | 6047 | 5880 |

Overall, Table 2 and Table 3 summarized the maximum tension strain, compression strain and shear strain value of the four composite beams, it was evident that the beams suffered higher shear strain and the beam with circle hole was more safety. The margins of the beams were verified with equation (1) and proved sufficient. As well as the maximum shear strain of composite parts appeared right at the opening edge in both two loads. It can be found that the open-hole web suffered high strain and complex strain distribution, an analyze of maximum stress around the holes were needed.

### 4.2 Stress around the opening

Fig.10 and Fig.11 illustrate the stress fields (major max) around different openings under the maximum shear load and the maximum bending-shear ratio load, respectively. It is observed from that the stress distributions around the hole are similar and there was significant increase in the stress around the holes, while the stress concentration position are various with the change of hole forms, while the beam with circle hole has the least value.

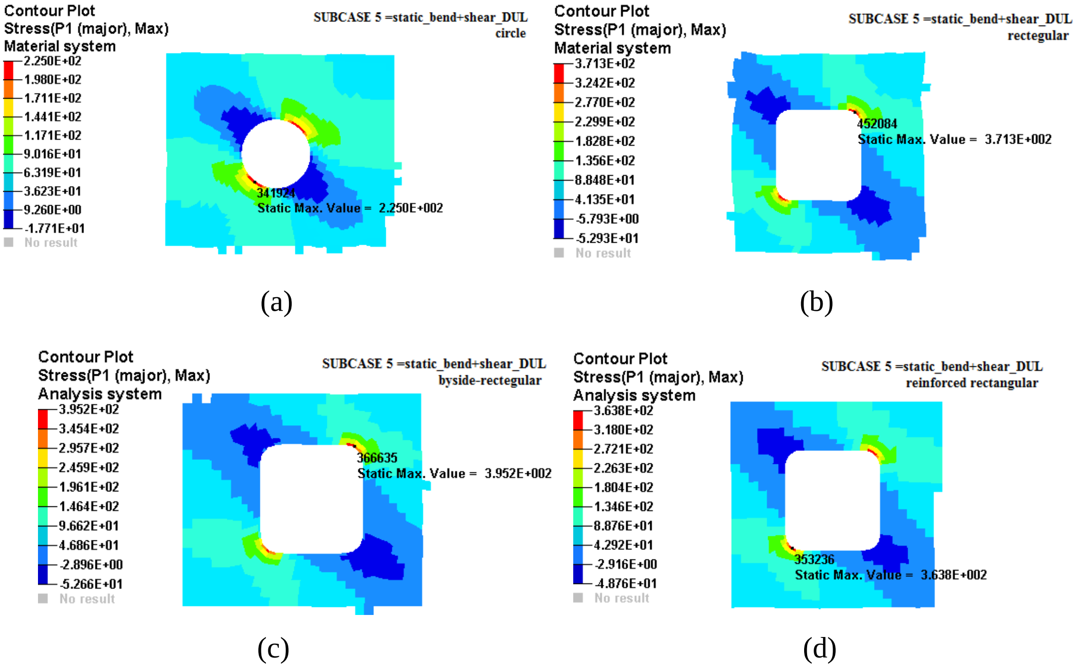



Figure 10: The stress fields around different openings under the maximum shear load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

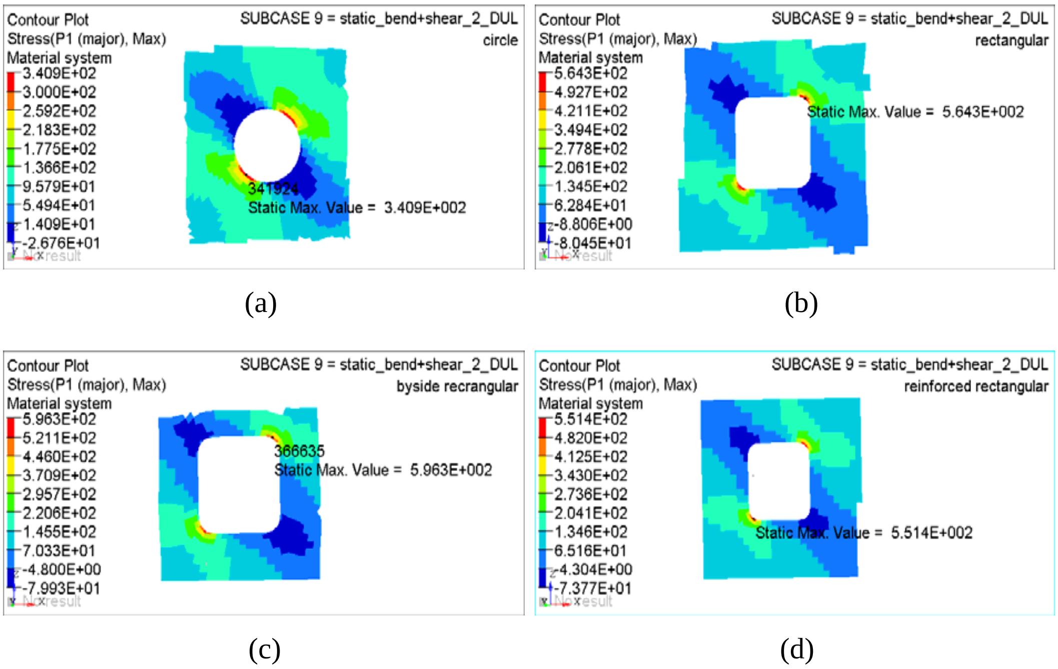



Figure 11: The stress fields around different openings under the maximum bending-shear ratio load: (a) circle hole, (b) rectangular hole, (c) eccentric rectangular hole and (d) rectangular hole with a strengthen.

Table 3 Comparison of the stress values under the maximum bending-shear ratio load and the maximum bending-shear ratio load..

| | | Circle hole | Rectangular hole | Eccentric rectangular hole | Strengthen rectangular hole |
|---|---|---|---|---|---|
| Stress(maximum shear load) | [MPa] | 225 | 371 | 395 | 363 |
| Stress( maximum bending-shear ratio load) | [MPa] | 340 | 564 | 596 | 553 |

Overall, Table 3 compares the maximum stress value of the four composite beams under the maximum bending-shear ratio load and the maximum bending-shear ratio load. The margins of the structure were calculate with the equation 2, and the margin values shows that the beam could well carry the loads. It is interesting to note that the maximum stress value of structure around the hole was nearly the same for the different rectangular hole shapes, a reinforced measure can increase the load capacity slightly. While for the beam with circle hole, the stress concentration of circle opening is about half of the rectangular opening.

## 5 CONCLUSION

In this paper, a numerical study of open-hole composite beam for a wing spar is presented. The representative effects of hole shape and distribution on bearing behaviour of beam are investigated. The differences of strain/stress filed and verification results between four types beam are summarized. The following conclusions can be drawn:

This composite beam structure with open-hole on web could well carry the design load for a wing spar. The form and distribution of the hole showed great influence on stress concentration around the hole. The beam with circle opening suffered lesser stress and had higher margin than the rectangular opening. An open-hole position move and a simple reinforced measure cannot obviously increase the load capacity. Through the study, it is demonstrated that this open-hole composite beam structure can be used for a composite wing spar structure.

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