Effect of low velocity impact on residual compressive strength of stiffened panel with welding residual stress

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Abstract. Al-Li alloy stiffened panel is the main structural form of aircraft fuselage. Laser welding will produce welding deformation and residual stress, on the other hand, low velocity impact will also affect the residual bearing capacity of stiffened panel structure. In this study, the nonlinear finite element (FE) method is used to simulate the laser welding process of stiffened panel, and the welding residual stress is directly introduced into the subsequent impact after compression (CAI) process of stiffened panel. The effects of different impact positions and different impact energy on the residual CAI strength of stiffened panel are studied. The results show that the impact damage has the greatest effect on the residual compressive strength of stiffened panel when the punch impacts the stiffener, and the greater the impact energy is, the greater the influence is.

1. Introduction

2099 Al-Li alloy is a kind of aluminum alloy with low density, high elastic modulus, high specific strength and high specific stiffness. The stiffened panel made of 2099 Al-Li alloy can not only meet the requirements of more and more complex aerospace service environment, but also meet the lightweight design concept of aerospace transportation tools.

The most important deformation of stiffened panels is uniaxial in-plane compression under external loads[1]. Scholars have done a lot of research on stiffened panel under compression load, and investigated the buckling and post buckling behaviors through experiments, numerical simulation and analytical methods[2-4]. In addition, impact, as a common condition in the service process of aircraft fuselage, such as the fall of maintenance tools during maintenance, hail and bird strike during service, will have a serious impact on fuselage. Scholars have conducted a series of research on stiffened panels under complex loads such as impact load and CAI through experiments and numerical simulation[1,5].

The traditional connection of T-stiffened panel components is mostly riveting, which not only causes the perforated damage of stiffened panel, reduces the strength of stiffened plate, but also increases the weight of stiffened panel. Therefore, laser welding as a high energy density welding technology is more widely used. The existing simulation of the compression performance of laser welded stiffened panel generally does not consider the influence of welding residual stress[2], or the residual stress and deformation are introduced into the stiffened panel in the way of equivalent initial defects[6], which inevitably deviates from the actual situation. Therefore, in view of the influence of
low velocity impact on the residual compressive strength of stiffened panel with welding residual stress, in this study, the complete laser welding process is simulated by sequential thermal mechanical coupling method. The residual stress obtained by welding is directly introduced into the subsequent impact and CAI process, and the residual compressive strength of stiffened panel with residual stress is studied.

2. Finite element model

2.1. Geometric model

In order to verify the residual compressive strength of Al-Li alloy stiffened panel after impact, the commercial FE software ABAQUS 2016 explicit dynamic solver was used to simulate the stiffened panel. The stiffened panel skin size is $440 \times 260 \times 2$ mm (long $\times$ wide $\times$ high). The length of the rib is 440 mm, and its height is 29 mm, the width of the upper flange is 16 mm, the thickness is 2 mm, and the weld is $1.5 \times 1$ mm (bottom $\times$ high) triangular prism. The dimension diagram and local diagram of stiffened panel are shown in Figure 1. The welding process is double beam laser welding at the same time, the welding power is 2400 W, the welding speed is 4 m/min, and the incidence angle is 30°.

![Figure 1. Dimension schematics of stiffened panel and local welds.](image)

The material of stiffened panel is 2099 Al-Li alloy, and the material composition is listed in Table 1. The constitutive model of Al-Li alloy is bilinear isotropic hardening elastic-plastic model. The temperature dependent thermal and mechanical properties are shown in Figure 2. The J-C damage model is selected as the damage model, and the damage parameters are listed in Table 2.

| Element | Cu   | Ti   | Li   | Fe   | Zn   | Si   | Mg   | Mn   | Zr   |
|---------|------|------|------|------|------|------|------|------|------|
| Proportion | 2.4-3.0 | ≤0.1 | 1.6-2.0 | ≤0.07 | 0.4-1.0 | ≤0.05 | 0.1-0.5 | 0.1-0.5 | 0.05-0.12 |

| D1     | D2    | D3    | D4    | D5    | Melting temperature | Transition temperature | Reference strain rate |
|--------|-------|-------|-------|-------|---------------------|------------------------|----------------------|
| Parameters | -0.13 | 0.256 | -0.47 | -0.012 | 1.97 | 624 | 20 | 1 |
2.2. Welding thermal analysis

Based on the transient heat transfer equation given in Equation (1), the welding process of stiffened panel is simulated by sequential thermal mechanical coupling method, that is, the node temperature of each loading step or each loading time point obtained by nonlinear transient thermal analysis is taken as the load of FE model, and the residual stress are calculated.

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + G = \rho C_p \frac{\partial T}{\partial t}
\]

where \( k_i \) (\( i = x, y, z \)) is the thermal conductivity in \( x, y \) and \( z \) directions, respectively. \( G \) is the heat generated in the control volume, \( \rho \) is the density of the material, \( C_p \) is the specific heat of the welding material. The base metal is assumed to be isotropic and its \( k_i \) is described as \( k_x = k_y = k_z = k \).

The heat source model adopted is the double ellipsoid heat source model proposed by Goldak [8], and the expression is Equation (2). The schematic of the heat source model is shown in Figure 3.

\[
q_f(x, y, z) = \frac{6\sqrt{3} f_f Q}{a_f b c \pi \sqrt{\pi}} \exp \left( \frac{-3x^2}{a_f^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2} \right), x \geq 0
\]

\[
q_r(x, y, z) = \frac{6\sqrt{3} f_f Q}{a_r b c \pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a_r^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2} \right), x < 0
\]

Among them, the shape parameter \( a_f = 1.2, a_r = 1.4, b = 1.3, c = 1.5 \), the heat source distribution coefficient \( f_f = f_r = 1 \), and \( Q \) is the effective power.

2.3. Grid generation

In the FE dynamic analysis, the impact of stiffened panel is simulated firstly, and then the stiffened panel is compressed by restart method. The mesh type of the FE model is C3D8R 8-node solid element. The convergence of the mesh is analyzed by taking the maximum equivalent strain after impact as the index, and the mesh size of the impacted part is set to 1 mm; In the welding process, the grid types of thermal analysis and force analysis are DC3D8 and C3D8 8-node elements, respectively. The heat gradient at the weld is high, the grid sensitivity is high, and higher accuracy is required, so the grid needs to be refined [9]. The mesh size of weld is 0.2 mm and that of heat affected zone is 0.4 mm. By dividing the transition grid, with the increase of the distance from the weld, the size of the grid gradually increases to 32.4mm, the total number of grids is 471931, and the number of nodes is 548284. The overall grid division of the stiffened panel is shown in Figure 4.
3. Results and discussion

3.1. Effect of impact location on residual compressive strength of stiffened panel with residual stress

25J impact energy was used to simulate the CAI of three locations of the stiffened panel. The three locations and damage are shown in Figure 5. The influence of impact damage at different locations on the residual compression strength of the stiffened panel is analyzed.
The compression damage and residual compressive strength of stiffened panel after impact are shown in Figures 6-7. The ultimate compressive strength was 174.9 kN for the stiffened panel without impact. When Position 1 was impacted, the initial impact damage extended along the weld until the stiffened panel failed. The residual compressive strength of the stiffened panel was 133.8 kN, which was 23.5% lower than that of the non-impact stiffened panel. When Position 2 was impacted, the final damage occurred at the weld after the instability of the stiffened panel. The residual compressive strength was 164.1 kN, and the ultimate strength was reduced by 6.2%. When Position 3 was impacted, the final damage was the damage of the stiffened panel. The residual compressive strength was 124.2 kN, and the ultimate strength was reduced by 29%.

Figure 7. Residual compressive strength after impact at different positions.

Figure 8. Residual compressive strength of stiffened panel under different energy.

The above results show that the ultimate strength of the stiffened panel decreases the most when it is impacted at Position 3, because the rib is the main load-bearing component. The second reduction of the ultimate strength is the impact on Position 1 with welding residual stress, which is due to the different stiffness of the rib and skin, resulting in different deflections. The resulting tensile stress and residual stress are superimposed, resulting in the initial impact damage extending along the weld, and the stiffened panel failure. The impact at Position 2 has the least effect on the ultimate strength of the stiffened panel. This is because the failure mode of the stiffened panel is buckling instability, and the local impact damage of the skin has little effect on the stability of the stiffened panel structure, so the reduction of the ultimate strength is small.

3.2. Effect of impact energy on residual compressive strength of stiffened panel with residual stress

The impact energy of 9J, 25J and 37J was used to compress the stiffened panel at Position 1. The residual compressive strength of the stiffened panel and impact damage are shown in Figures 8-9.

Figure 9. Impact damage of stiffened panel under different impact energy.

When the punch impacted the stiffened panel with 9J, 25J and 37J energy, the residual compressive strength of the stiffened panel was 150.3 kN, 132.2 kN and 130.7 kN respectively. Compared with the non-impact stiffened panel, the ultimate strength of the stiffened panel was reduced by 14.1%, 24.4%...
and 25.3% respectively. With the increasing of impact energy, the initial impact damage increased, and the residual compressive strength of stiffened panel decreased sharply. When the energy of 25J was used to impact the stiffened panel, it had been found that the stiffened panel skin had obvious damage. After the energy of 37J was used to impact the stiffened panel, the initial impact damage of the stiffened panel was obviously larger than that of 25J. However, the residual compressive strength after the impact of the two kinds of energy was not different, only 0.9%, because the initial impact damage of the metal stiffened panel has a greater effect on the structural stability of the stiffened panel, and a smaller influence on the strength of the stiffened panel, which can be almost ignored. However, when the impact energy continues to increase and the rib is damaged, the residual compressive strength will decrease.

4. Conclusion
In this study, the thermal sequential coupling method is used to simulate the laser welding process of stiffened panel. The residual stress produced by welding is directly introduced into the subsequent dynamic analysis process, the FE simulation of low velocity impact and CAI of stiffened panel with welding residual stress is carried out, and the influence of different impact position and impact energy on the residual compressive strength of stiffened panel with welding defects is analyzed. The results are as follows.

- The CAI simulation for different positions of the stiffened panel with the same energy is carried out. The results show that the initial impact damage has the greatest impact on the residual compressive strength of the stiffened panel when the punch impacts the stiffener, the second effect is when the punch impacts the weld, and the least effect is when the skin is impacted;
- It is found that the residual compressive strength of stiffened panel decreases with the increase of impact energy when the same position (weld) of the stiffened panel is impacted with different energy. When the impact energy reaches the failure energy of the stiffened panel, the reduction degree of the residual compression strength of the stiffened plate decreases.

Acknowledgments
The authors thank the National Natural Science Foundation of China (Nos. 11772081, 11972106, 11635004).

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