Numerical investigation of buckling behaviour of grid stiffened panel with opening during creep age forming

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Abstract. This study focuses on the prediction of the formability of the integrally stiffened panels with opening due to buckling during the loading stage and heating stage of the creep age forming (CAF) process. The simplified model of integrally stiffened panels with opening was established to investigate the buckling behavior of the stiffened panel subjected to pure bending moment at room temperature and ageing temperature. The influence of the main geometrical parameters (stiffener thickness and stiffener height) on the critical buckling stress and critical buckling strain of the stiffened panel at the two temperatures was studied by finite element simulation. With the increase of the stiffener thickness and the decrease of the stiffener height, the critical buckling stress will increase to about 570 MPa at room temperature and 475 MPa at ageing temperature, which makes the formability limit increase correspondingly. When the stiffened panel is in the elastic region, the non-dimensional critical buckling coefficient is reduced by 20%, compared with the traditional stiffened panel. When the stiffened panel enters the plastic region, the critical buckling strain increases and the forming limit enhances accordingly. The research results offer a significant reference for the structural optimization design of the stiffened panel, presenting a simplified approach for studying other special shapes of stiffened panels, which is helpful to ensure that the workpiece will not be buckled during the forming process.

Introduction

Integrally stiffened panels with opening have a highly potential to replace conventional riveting stiffened panel in aerospace and marine structures [1], such as the aircraft fuselage, to achieve lightweight [2], provide ventilation channels, and accommodate features such as pipes or cables. Creep ageing forming (CAF), as a stiffened panel forming process, plays an important role in meeting the industrial demand [3,4]. The workpiece is loaded by bending moment at room temperature and heated to the ageing temperature for creep process, and then unloaded when the deformation is finished [5]. In the forming process, the framed part of the stiffened panel is under high pressure stress and will result in buckling [6]. Therefore, it is necessary to simplify the integrally stiffened panels with opening and investigate the buckling behavior of the key region at room temperature and ageing temperature in order to predict the forming limit.

The buckling behavior of stiffened panels subjected to bending moment or shear load has been studied extensively. Zhou et al. [7] successfully predicted the forming limit of the traditional stiffened panel by using the buckling modes simulated by linear finite element method to obtain the initial defects, and carried out nonlinear finite element simulation based on the Riks method.

Lian et al. [8] studied the buckling behavior of conventional stiffened panels under shear load, and the results showed that the increasing of the equivalent skin thickness leads to the increasing of the critical buckling stress. Based on theoretical calculation, Liu et al. [9] established the

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enhanced elastoplastic damage coupled model of stiffened panel under uniaxial compression. Based on buckling test, Pevzner et al. [10] studied buckling behavior of stiffened panels with different cross sections, such as J-form stiffeners and T-form stiffeners. However, few researchers have studied the buckling behavior of special shapes of stiffened panels, such as panels with opening.

In this study, the buckling behavior of integrally stiffened panels with opening subjected to pure bending at room temperature and ageing temperature was studied by finite element simulation, and the forming limits during the loading stage and heating stage of CAF were predicted successfully. Firstly, the overall buckling simulation of the integrally stiffened panel with opening was carried out, and it is found that the buckling occurs mainly in the position between two transverse bars. Based on the simulation results, the key region of the integrally stiffened panel with opening model was simplified, and the corresponding simulation simplified model was established. The influence of different geometrical parameters, such as stiffener thickness and stiffener height, on the buckling critical stress and buckling critical strain of stiffened panel was studied by Abaqus software. At the same time, non-dimensional critical buckling coefficient k_{cr} is introduced to compare the forming ability of the stiffened panel with opening with the traditional stiffened panel.

Problem definition

In this paper, the buckling behavior of the integrally stiffened panel with opening under pure bending moment M_x is studied. The integrally stiffened panel with opening is shown in Fig. 1. The overall simulation with whole stiffened panel was carried out by linear finite element method, and it is found that the buckling mainly occurs in the position between the two transverse bars, as shown in Fig. 2. The top of the stiffeners experienced high pressure stress during the forming process of the integral stiffened panel, leading to the potential buckling and instability deformation of the longitudinal stiffeners at both ends of the center frame, as illustrated in Fig. 1, resulting in the forming failure of the integral panel. In the simulation process of this paper, the key region of the integrally stiffened panel model was simplified. The simplified model is shown in Fig. 3, where the geometric parameters include the distance between the two transverse stiffeners a, the length of the transverse stiffeners b, the thickness of the skin t_{sk}, the height of the longitudinal stiffeners h and the thickness of the stiffened panel t_{st}. The simplified model can represent the buckling behavior of the whole stiffened panel. In this study, some geometric parameters of stiffened panels were fixed as a = 140 mm, b = 90 mm, $t_{st}/t_{sk} = 1$.

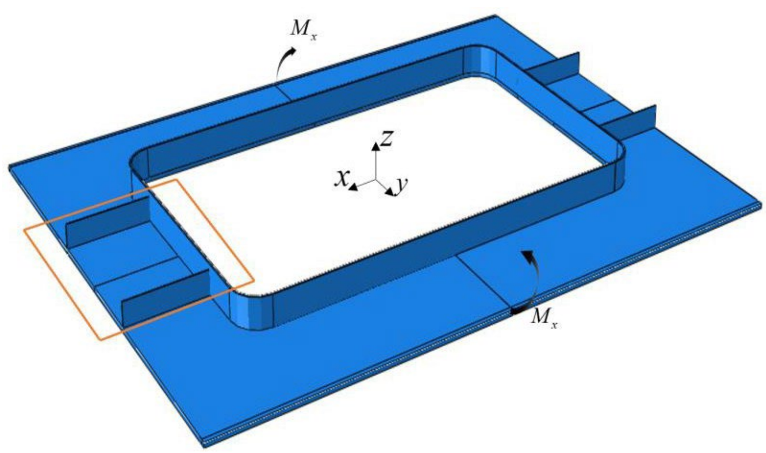


***Fig. 1**: Integrally stiffened panels with opening subjected to pure bending moment*

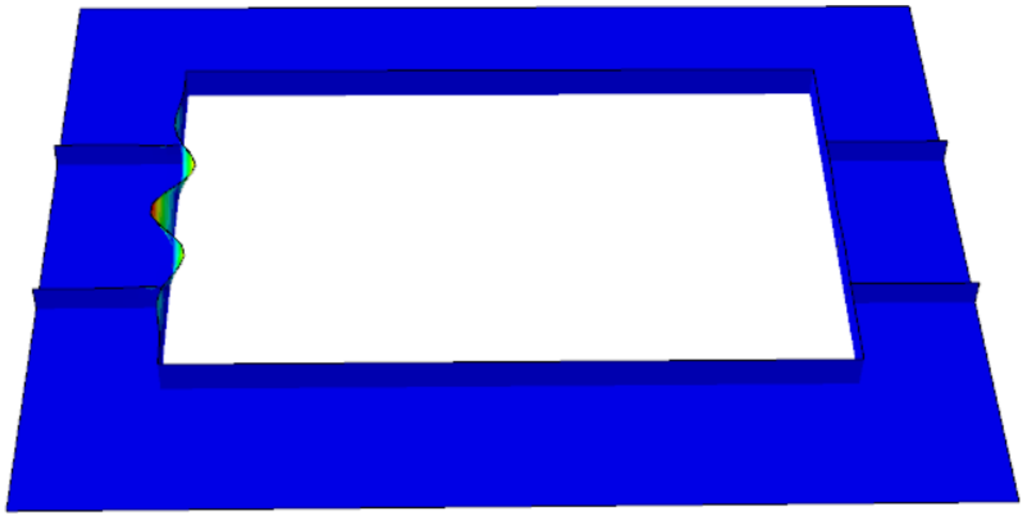


Fig. 2: *The overall simulation of integrally stiffened panel*

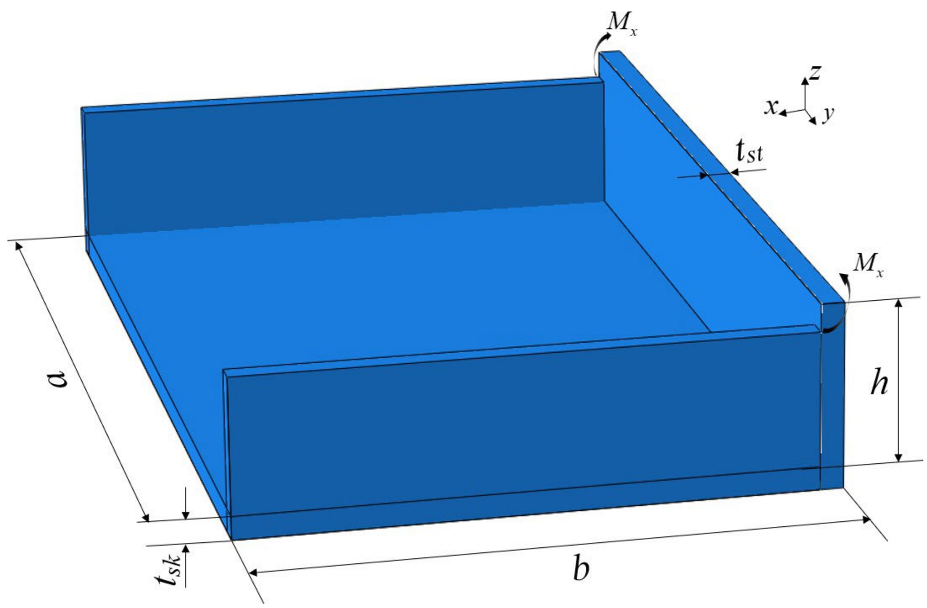


Fig. 3: *Simplified FE model of integrally stiffened panels with opening*

Finite element simulation

Material and properties

The integrally stiffened panel material used in this paper is aluminum alloy 7050. In industry, in order to achieve the T7451 state of aluminum alloy, it is often aged at 120 °C for 4 to 6 hours after solid solution heat treatment, and then aged at 160 °C for about 20 h [11]. Thus, in this study, after solution heat treatment (475, 1h) and quenching, the material was aged at 120 ℃ for 5 h. The tensile test was carried out at room temperature and 160 ℃ respectively. The material properties of AA7050 are shown in Table 1. The engineering stress-strain curves at room temperature (RT) and ageing temperature (160 ℃) are shown in Fig. 4. It can be seen from Fig. 4 that the elastic modulus of the alloy at two temperatures is basically the same, and the yield strength decreases under high temperature conditions.

Table 1. *Mechanical properties for AA7050-T7451 at the room temperature and 160 ℃*

Temperature	E(GPa)	σ_y(MPa)
Room temperature	73.07	537.4
160 ℃	73.07	457.5

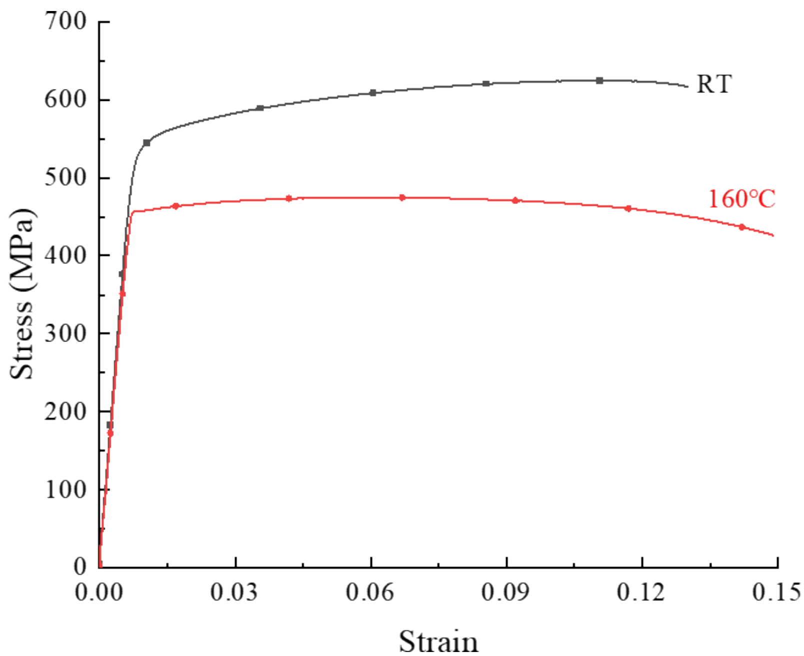


Fig. 4: *Engineering stress-strain behaviour of AA7050 at the room temperature (RT) and the ageing temperature (160 ℃)*

FE method

The simplified finite element model is shown in Fig. 5. The R4S shell element is used for modeling, which can obtain higher solution accuracy [12]. The stiffened panel is subjected to pure bending moments at two transverse edges. The two loading edges of the model are constrained to the simply supported condition: the displacement of the two lateral edges of the fixed skin in the z-direction, the middle line of the skin in the y-direction, and the two transverse edges of the longitudinal stiffener in the x-direction. At room temperature and ageing temperature, different elastic-plastic parameters are assigned to the material. The room temperature simulation applied the room temperature material data, and the high temperature simulation applied the corresponding data. In the simulation process, the elastic modulus $E = 73071$, Poisson's ratio $\nu = 0.33$ [13].

In the process of finite element simulation in this paper, the model is simplified based on the result of linear finite element simulation, which has been mentioned in Fig. 2. In the simplified model, the pure bending is applied on the stiffened panel, and the longitudinal stiffened part between the two transverse stiffeners is the main region of buckling instability. Therefore, in this paper, the stiffener thickness and stiffener height are selected as variables to carry out research. The stress at the midpoint of the longitudinal stiffener is taken as the buckling stress of the simplified model, and the ratio of the displacement at both ends of the longitudinal stiffener to the length of the longitudinal stiffener is defined as the average strain.

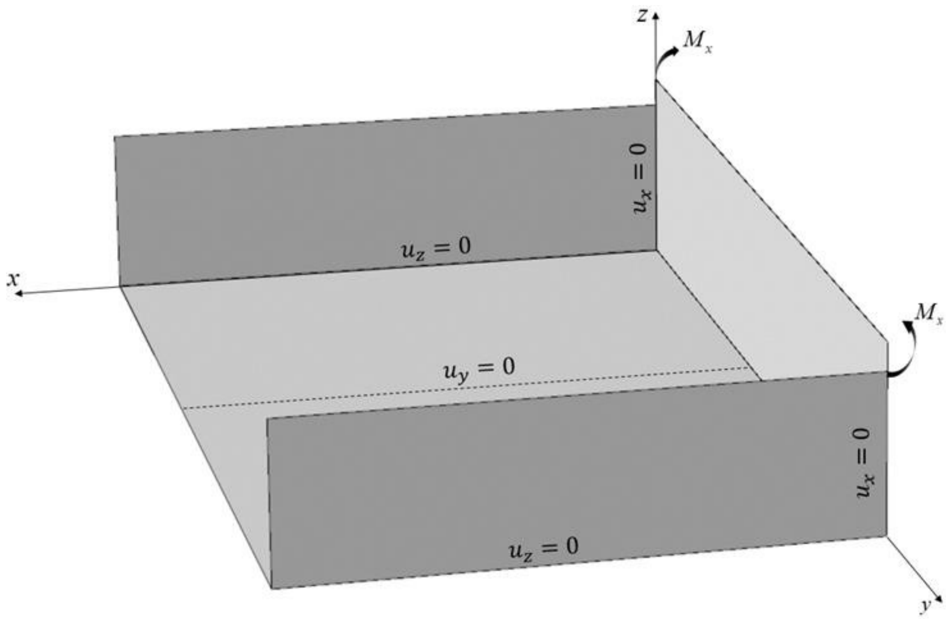


Fig. 5*: Boundary conditions of Simplified FE model of integrally stiffened panels with opening*

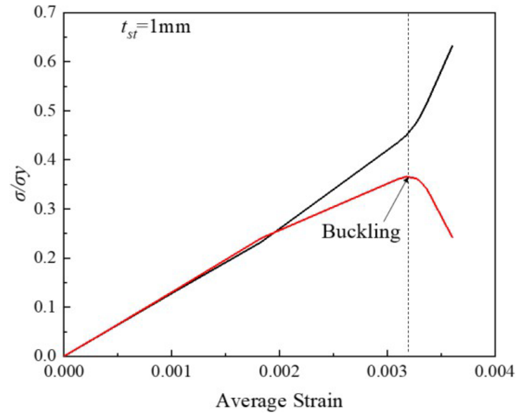
Results and discussion

Two sets of finite element simulation at room temperature and 160 °C, the commercial software Abaqus was used to investigate the buckling behavior of simplified model of the integrally stiffened panel under different geometric parameters (thickness and height of the stiffened panel), and to predict the buckling critical stress and strain of the stiffened panel during loading and heating.

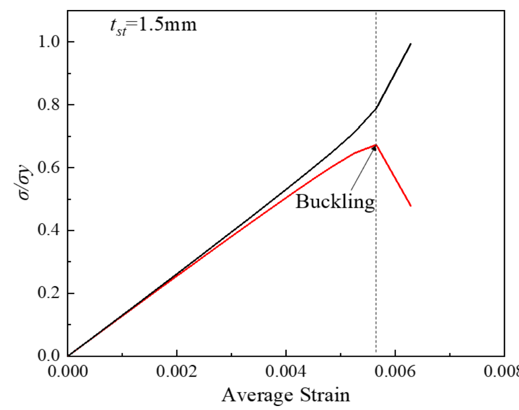
Effect of stiffener thickness

In this section, based on the results of finite element simulation, the effects of the stiffener thickness t_{st} at RT and 160 °C on the buckling behavior of a simplified model under bending are discussed. In the simplified model, the ratio of bottom skin length *a*, bottom skin width *b*, stiffener height *h*, skin thickness to stiffener thickness were taken as 140 mm, 90 mm, 20 mm, and 1.0, respectively. The test range of stiffener thickness is from 1 mm to 2.8 mm. The average compressive stress and average strain at the top midpoint of the stiffener are obtained by finite element simulation. Fig. 6 shows the relationship between the average normalized stress $\sigma / \sigma_y$and the average strain on the left and right sides of the top midpoint of the stiffener under RT with different thickness of the stiffener.

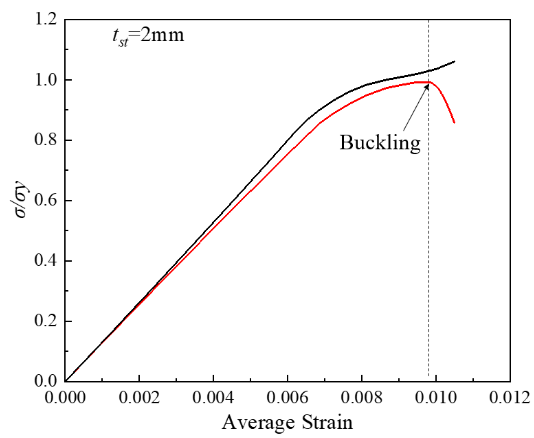
When t_{st} = 1, 1.5 mm, the average stress increases linearly with the increase of the average strain in the initial stage, and remains stable when buckling occurs. When the stiffened panel is stressed in the elastic zone, the bifurcation point is easy to observe and calculate. As shown in Fig. 6, when the average strain reaches 0.3% and 0.6% respectively, the buckling stresses under corresponding conditions are obtained, which are 196.7 MPa and 388.1 MPa respectively. However, when t_{st} = 2, 2.5, 2.8 mm, the stress of the stiffened panel first lies in the linear zone, and when it enters the plastic zone, the stress increases slightly with the increase of the average strain. When the average strain reaches 0.9%, 1.5% and 2.2%, respectively, the corresponding buckling stresses are 533.2 MPa, 573.4 MPa and 583.5 MPa. At the same time, due to the increase of the stiffener thickness, the buckling phenomenon is gradually less obvious.



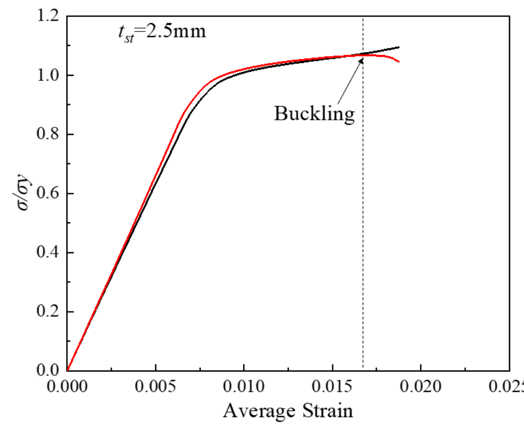
(a) t_{st} = 1 mm



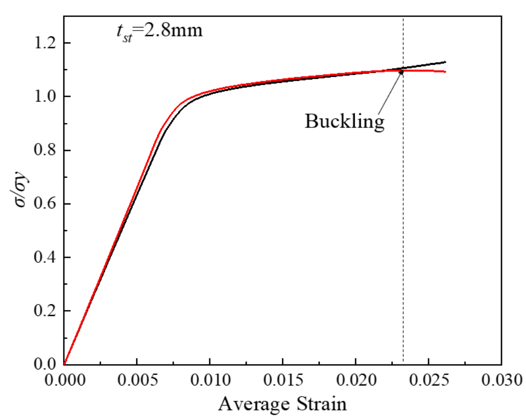
(b) t_{st} = 1.5 mm



(c) t_{st} = 2 mm



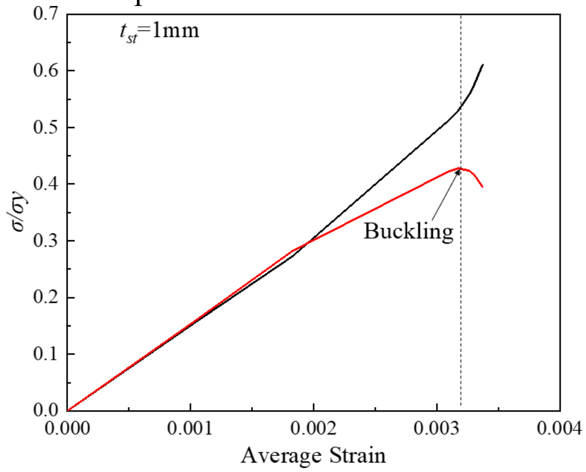
(d) t_{st} = 2.5 mm



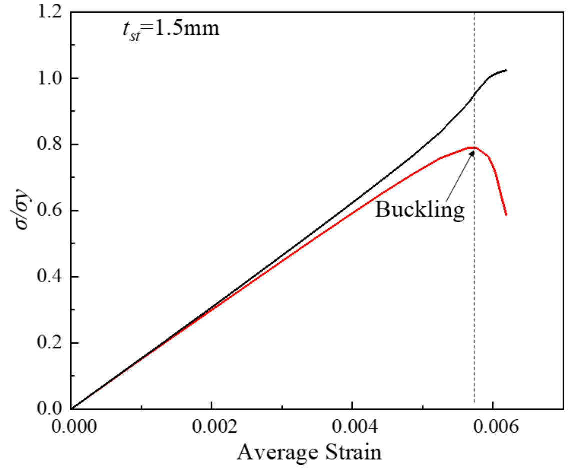
(e) t_{st} = 2.8 mm

Fig. 6*: Average normalised stress of left side (red line) and right side (black line) of top stiffener versus average strain obtained from non-linear FE simulations at the room temperature with different stiffener thickness.*

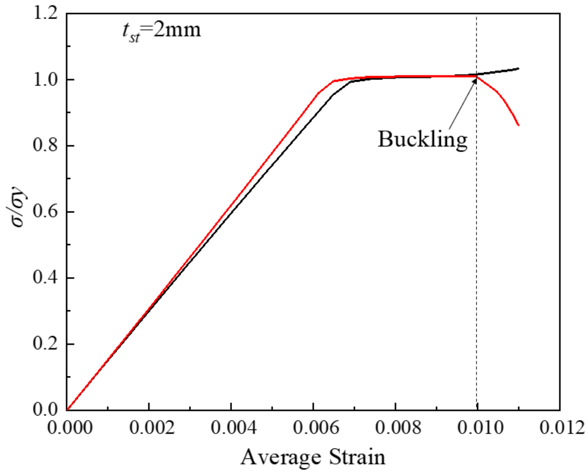
Fig. 7 shows the relationship between the average normalized stress and the average strain at the left and right sides of the midpoint at the top of the stiffener at 160 °C. When t_{st} = 1, 1.5 mm, the buckling of the stiffened panel occurs in the elastic zone, and the buckling stresses are 196.1 MPa and 368.7 MPa, respectively. When t_{st} = 2, 2.5 and 2.8 mm, the buckling of the stiffened panel occurs in the plastic zone, and the buckling stresses are 462.4 MPa, 471.8 MPa and 486.7 MPa, respectively. The variation trend of average normalized stress at ageing temperature is similar to that at room temperature.



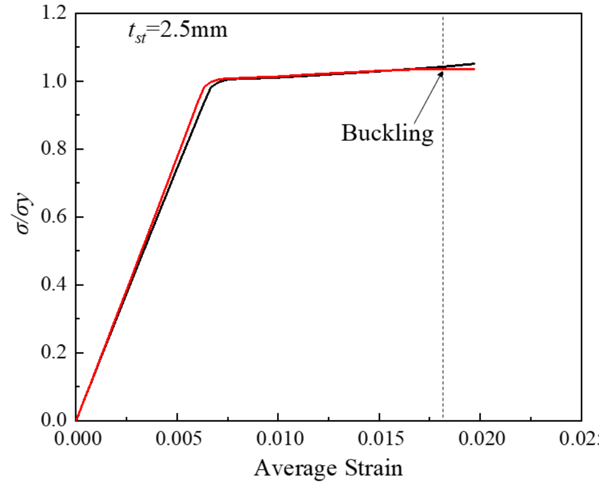
(a) t_{st} = 1 mm



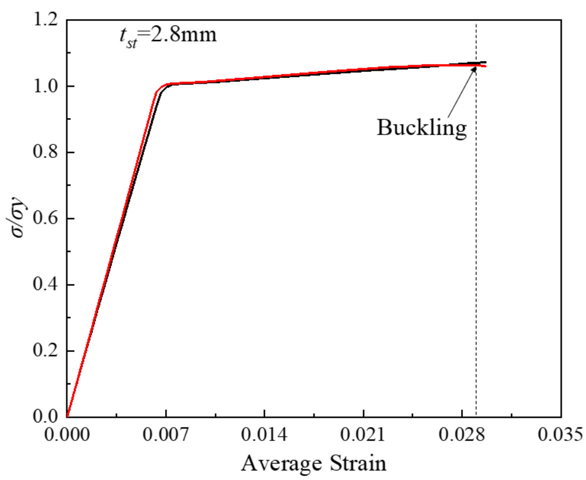
(b) t_{st} = 1.5 mm



(c) t_{st} = 2mm



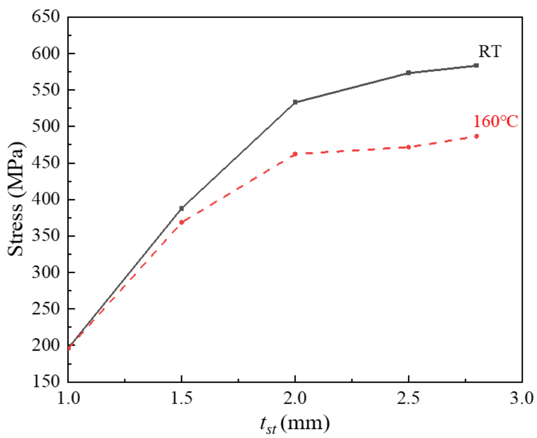
(d) t_{st} = 2.5 mm



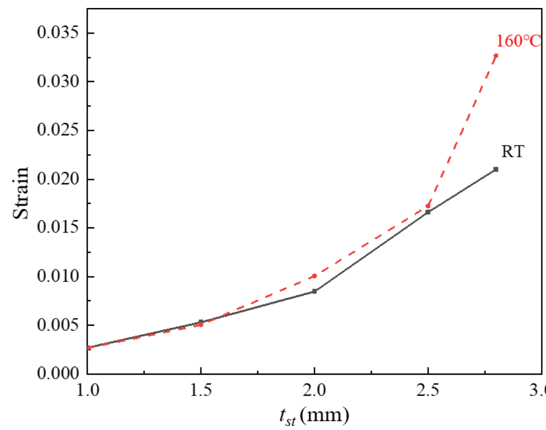
(e) t_{st} = 2.8mm

Fig. 7: *Average normalised stress of left side (red line) and right side (black line) of top stiffener versus average strain obtained from non-linear FE simulations at 160 ℃ with different stiffener thickness.*

The critical buckling stress and critical buckling strain under different stiffener thickness at RT and 160 ℃ are shown in Fig. 8. Due to the same elastic material parameters, the buckling critical stress and critical strain increase similarly with thickness at two different temperatures. When the structure enters the plastic zone, the critical buckling stress at ageing temperature is less than that at room temperature, and the average reduction is about 15%. However, greater buckling strain is produced at ageing temperature, which is about 40% higher than that at room temperature. This increases the forming limit. Therefore, in the case of plasticity, the stiffened panel can be heated first and then deformed by loading.



(a) Evolution of buckling critical stress with increased stiffener thickness



(b) Evolution of buckling critical strain with increased stiffener thickness

***Fig. 8**: Critical buckling stress and critical strain versus stiffener thickness t_{st} at the room temperature (solid line) and 160 ℃ (dashed line)*

For the elastic region, the non-dimensional critical buckling coefficient k_{cr} is introduced to study the influence of geometric size and temperature on the buckling response of the stiffened panel. The expression is as follows [14,15]:

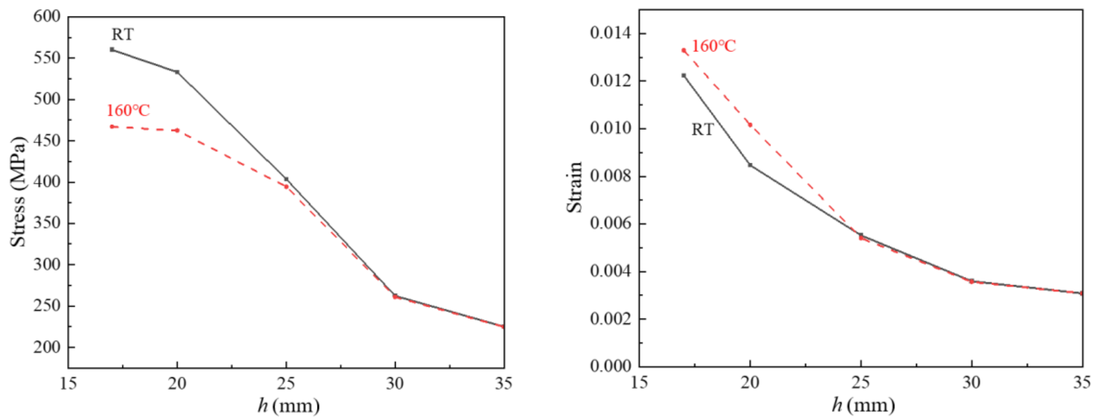
$$k_{cr} = \frac{12(1-\nu^2)\sigma h^2}{E\pi^2 {t_{st}}^2} \tag{1}$$

Where ν is Poison's ratio, E is elastic modulus, and σ is the corresponding buckling stress under t_{st}, 0.33, 73071, and 196.7 respectively.

The results show that when t_{st} = 1 mm, k_{cr} = 1.17 for stiffened panel with opening. For traditional stiffened panels, when t_{st} = 1 mm, k_{cr} = 1.5 [14]. This shows that for stiffened panels with empty frames, although the weight of the stiffened panel is reduced, the buckling stress is inevitably reduced. Therefore, it is necessary to choose the right combination of stiffened thickness and height to ensure the forming limit under the premise of meeting the lightweight.

Effect of stiffener height

In this section, based on the results of finite element simulation, the effects of the stiffener height h at RT and 160 ℃ on the buckling behavior of a simplified model subject to bending are discussed. In the simplified model, the length of the bottom skin a, the width of the bottom skin b, the stiffener thickness t_{st}, the ratio of the skin thickness to the stiffener thickness were taken as 140 mm, 90 mm, 2 mm and 1.0, respectively. Stiffener height test range is from 17 mm to 35 mm. The critical buckling stress and critical buckling strain decrease with the increase of stiffener height. At both temperatures, when the stiffener height is less than 25 mm, the buckling occurs in the elastic region. When the stiffener height is greater than 25 mm, the buckling occurs in the plastic region, and at the same stiffener height, the critical buckling stress decreases by about 16% and the critical buckling strain increases by about 9%.



(a) Evolution of buckling critical stress with stiffener height increased

(b) Evolution of buckling critical strain with stiffener height increased

Fig. 9*: Critical buckling stress and critical strain versus stiffener height at the room temperature (solid line) and 160 ℃ (dashed line)*

Conclusions

In this study, the key region in the forming process of the integrally stiffened panel was simplified, and the forming limits in the loading and heating stages of the CAF process were predicted by finite element simulation. The elastoplastic buckling behavior of AA7050 under the pure bending moment at room temperature and ageing temperature (160 ℃) was studied. The reduction of the stiffener height or the increase of stiffener thickness can help to avoid buckling instability in the forming process. In the elastic region, the non-dimensional critical buckling coefficient k_{cr} is 1.16 for the stiffened panel with opening. It reduced by 20%, compared with the traditional stiffened panel, which is 1,5. However, this kind of stiffened panel more meets the demand of lightweight. When the stiffened panel enters the plastic zone, the increase of temperature will enhance the forming limit. Therefore, if the buckling does not occur during the loading process, then the buckling will not occur during the heating process, and the forming limit of the workpiece can be improved by heating before loading

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