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Life prediction model of creep-rupture and creep-buckling of a pyramidal lattice truss panel structure by analytical and finite element study

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ABSTRACT

The creep failure lives of a pyramidal lattice truss panel structure at compressive and tensile loads have been investigated by theoretical and finite element methods. Two analytical models are derived to calculate the life of creep-rupture and creep-buckling. The results reveal that the creep-rupture life is highly sensitive to the geometry dimensions. With the decreases of the stamping angle, cutting angle, truss length and the increases of the truss width and thickness, the creep-rupture life decreases significantly. The creep-buckling model presents that the creep-buckling life can be improved by increasing the width and thickness of truss and decreasing the length of truss. A synthetically analytical model combines the creep-rupture and creep-buckling is proposed to predict the creep failure time accurately. The transition mechanism from creep-buckling to creep-rupture is also extensively studied. Creep-buckling is the dominant failure mechanism as the applied stress approaches the critical stress. The solid truss is inclined to creep-rupture when the compressive stress is smaller than the critical stress.

1. Introduction

Pyramidal lattice truss panel structure is a type of lightweight material with high strength and has been widely perceived as one of the most perspective multifunctional material [1–8]. Because of its high efficiency of heat transfer, it has been designed as compact heat exchangers at high temperature gas reactor (HTGR) and modern steam turbine in recent years [9–14]. Creep is the primary failure mode at elevated temperature, and a comprehensive creep design method is highly desirable to develop [15].

The lattice truss panel structure is a periodic cellular material, and two classical models have been proposed to characterize the creep strain rate of cellular material, i.e., GA model and HD model. Firstly, Gibson and Ashby [16] derived an analytical expression (GA model) to predict the creep rate of honeycombs basing on the assumption that the bending of solid strut perpendicular to the compressive load is the dominant deformation mechanism. The steady creep rate and creep failure time for a closed-cell aluminum foam has been investigated by Andrews et al. [17], and the results indicate that the creep property of foam materials is impacted significantly by the strut dimension and creep parameter. Fan et al. [18] investigated the uniaxial and multiaxial creep behavior of low density open-cell foams and proposed a modified GA model by taking the mass at strut node into account. The analytical model agrees well with the simulation results. Based on the HD model, Su et al. [19] developed an analytical model to predict the creep rate of the imperfect honeycombs. The results show that the creep rate of imperfect honeycombs depends on the defects fraction as well as the type of the missing truss. Secondly, Hodge and Dunand [20] (HD model) proposed another analytical model basing on the assumption that the creep deformation is mainly induced by the vertical strut, and the effect of horizontal strut is ignored. Jiang et al. [21] developed an analytical model (one of the modified HD model) to accurately calculate the equivalent creep strain rate of an X-type lattice truss panel structure. They found that the deformation of the X-type structure is mainly caused by the creep deformation of the vertical truss, and the creep rate is greatly affected by the geometrical conditions. Based on the GA and HD models, Boonyongmaneerat and Dunand [22] developed a set of theoretical expressions to investigate the creep rate of the metallic foams. The results indicate that the dominant creep deformation mechanisms of the strut transform from bending to shearing, and then to compression as the relative density increases. Monkman and Grant [23] proposed an empirical relationship between the minimum creep rate and rupture life at elevated temperature by analyzing the steady state creep rate. A modified expression to correlate the creep-rupture life and the minimum creep rate according to the rupture strain was developed by Dobes and Milicka [24]. This relation is well-known as the modified Monkman-Grant relationship (MMGR). Andrews et al. [16] and Andrews et al. [17] proposed a model to calculate the creep-rupture life of the foams based on the Monkman–Grant relationship. The results indicate that the creep-rupture life can be predicted accurately when the creep rate and creep constants are determined. A creep-rupture model of open-cell foams has

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been derived Chen and Huang [25]. The results indicate that the creep-rupture time is sensitive to their cell structural imperfection.

The creep-buckling is also a potential failure mode when the pyramidal structure is compressed at high temperature [26]. By investigating the collapse failure of cellular foams, a theoretical expression correlating the critical stress and the creep-buckling time was derived by Cocks and Ashby [27]. Lin and Huang [28] investigated the compressive creep properties of the hexagonal honeycombs and derived a set of formulas to predict the elastic buckling strength and the creep-buckling life. The results show that the solid distribution is dominant influencing factor for the creep-buckling life, and the failure mechanism changes from creep-bending to creep-buckling as the relative density increases. Chen and Huang [29] found that the creep-buckling life is highly affected by the structural imperfection relative density and creep constants. The dominant compressive creep failure mode is creep-buckling when the normalized stress approaches 1, however, it transformed to creep-bending gradually with the decrease of compressive stress.

Although the creep behavior of the cellular materials has been studied extensively in recent years, how to calculate the creep-rupture and creep-buckling life is still unclear for the lattice truss panel structure. Therefore, in this paper, we proposed two analytical models to study the creep-rupture and creep-buckling failure time of a pyramidal lattice truss panel structure. Moreover, how the geometrical parameters affect the creep life has been studied fully. Finally, a modified formula is derived to illuminate the relationship between the creep failure life and the required normalized stress.

2. Creep parameters

The material of the pyramidal structure is Hastelloy C276 and the creep behavior obeys the power-law equation:

$$\dot{\varepsilon}_c = B\sigma^n \tag{1}$$

where $\dot{\varepsilon}_c$ is the steady-state creep rate (h^{-1}), σ is the uniaxial stress (MPa), B and n are material constants. In our previous work [21], the creep test of Hastelloy C276 has been performed at 600 °C, and the creep constants B and n are 1.26×10^{-28} $\mathrm{MPa}^{-n}\mathrm{h}^{-1}$ and 9.63, respectively. The solid truss obeys the Monkman–Grant relationship [23,24]:

$$t_r \cdot (\dot{\varepsilon}_{\min})^m = C \tag{2}$$

where t_r is the creep-rupture life, $\dot{\varepsilon}_{\min}$ is the minimum creep strain rate of solid material at steady stage, and m and C are creep constants. The Monkman-Grant relationship is developed to obtain creep-rupture parameters by taking logs of both sides of the Eq. (2).

$$\lg(t_r) = -m\lg(\dot{\varepsilon}_{\min}) + \lg C \tag{3}$$

As shown in the Fig. 1, the creep-rupture parameters C and m are fitted by the minimum rate and the creep-rupture time based on the least square method, which are 0.01 and 1.2847, respectively.

3. Theoretical analysis

3.1. Creep-rupture model

In our previous work [21], the creep behavior of the X-type structure loaded in tension has been studied, and an accurate analytical model was proposed to predict the creep rate. Based on the same method, the equivalent creep strain rate for the pyramidal structure loaded in tension is proposed as following:

$$\dot{\varepsilon}_t = B\left(\frac{\left(l - \frac{d}{\cos(\alpha/2)\cos(\beta/2)}\right) wd\cos(\alpha/2)\cos(\beta/2)}{\left(l\sin\frac{\beta}{2} + w/\cos\frac{\beta}{2}\right)\left(l\cos\frac{\beta}{2}\sin\frac{\alpha}{2} + 2w - d\cot(45^\circ + \frac{\alpha}{4})\right)\left(l\cos\frac{\beta}{2}\cos\frac{\alpha}{2} + d\right)}\right)^{-n}\sigma^n \tag{4}$$

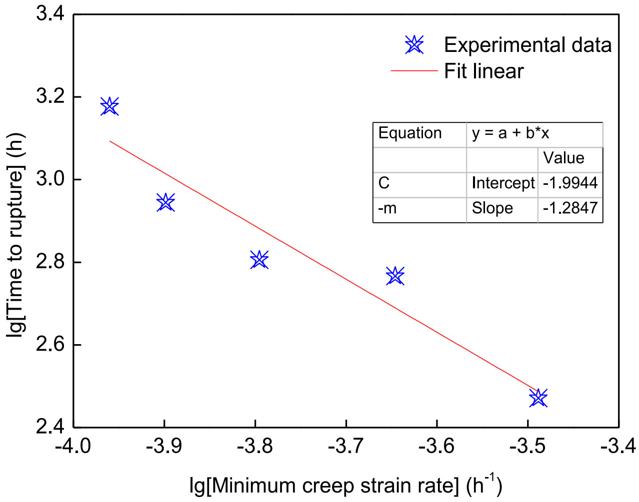

Fig. 1. Linear fit to creep-rupture time vs. the minimum creep strain rate on a log-log scale.

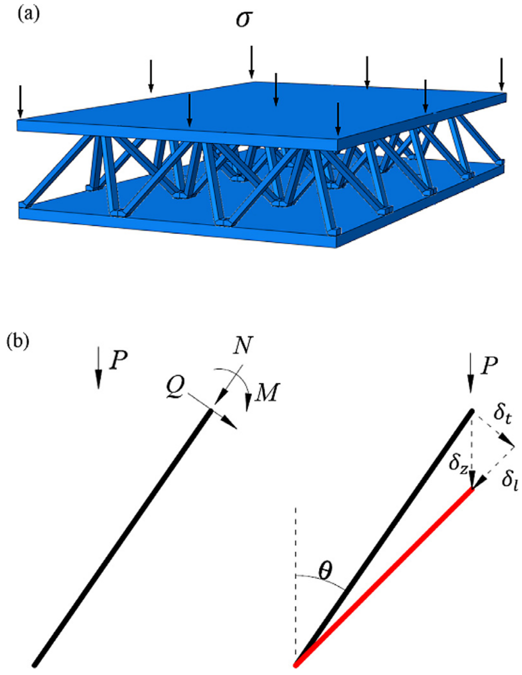

Fig. 2. Schematic of a pyramidal lattice truss panel structure (a) and the forces of the truss (b). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

where α, β, d, w and l are the stamping angle, cutting angle, truss thickness, truss width and truss length, respectively.

Fig. 2a shows a schematic of a pyramidal structure made of two metal sheets and periodic pyramidal cell. A constant pressure stress is perpendicularly imposed on the face sheet at elevated temperature. It assumes that the truss joint region is rigid, and the creep rate of the pyramidal structure is equal to the deformation rate of each truss. The forces of the truss are shown in Fig. 2b. The force P imposed on the truss are decomposed into longitudinal force N, shear force Q and moment M. The red and black lines denote the undeformed and deformed truss, re-

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