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Research paper

# Collapse criteria for high temperature ceramic lattice truss materials

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## HIGHLIGHTS

- High temperature failure criterion of lattice truss structure was proposed.
- Tensile fracture and buckling control failure of ceramic lattice truss structure.
- High temperature buckling is the key to design high temperature lattice structure.

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## ABSTRACT

Based on the temperature dependent behaviors of the Young's modulus and the strength of high temperature ceramics, temperature dependent failure characteristics of high temperature ceramic lattice truss materials were analyzed to build temperature-dependent failure theory. In compression, compression fracture and buckling are the competing failure modes. In shearing, tensile fracture and buckling are the competing failure modes. High temperature softening of the ceramic strut induces fatal buckling collapse for the lightweight lattice truss structure at ultra-high temperature. Collapse criteria under different planar stress states were built and are supported by high temperature experiments. Instructed by the criteria, collapse surfaces consisting of fracture surface and buckling surface were plotted and give helpful suggestions to design high temperature resistant as well as lightweight lattice truss ceramic composites.



## 1. Introduction

Hypersonic vehicles flying at speeds above Mach 7 have been extensively studied over the last decade. Sharp leading and trailing edges, nose cones and some other thermal protection systems (TPSs) designed for these hypersonic vehicles are subjected to severe aerodynamic heating during the launch and re-entry flight. To ensure the flight safety and protect the structures within acceptable temperature limits, TPS must be high temperature tolerant and lightweight [1–3]. For example, the TPS component made of C/SiC has been applied as an integral part of the Russian EXPRESS reentry capsule [4] and nose cap structure of NASA's X-38 [5].

To make TPS lighter, $ZrB_2$–SiC-graphite (ZSG) [6] and $ZrO_2$ [7] planar truss-core sandwich panels were proposed and fabricated for potential TPS applications, as shown in Fig. 1. The compression strength of the ZSG corrugated panel at 1600 °C is 17 MPa with a density 2.0 g/cm$^3$, which is only 40.6% of the ZSG bulk material [6], exhibiting an excellent combination of lightweight and load carrying. Wei et al. [8,9] also proposed an innovative design of pyramidal lattice composites with high temperature C/SiC ceramics as constituent for the purpose of TPS design, as shown in Fig. 1. Song et al. [10] made a high temperature C/SiC composite sandwich structure with stitched lattice truss core. Fu et al. [11] fabricated silicon/silicon carbide ceramic lattice composites by the three-dimensional printing (3DPTM) from Si/SiC/dextrin powder blends. The porous preforms exhibit excellent infiltration behavior

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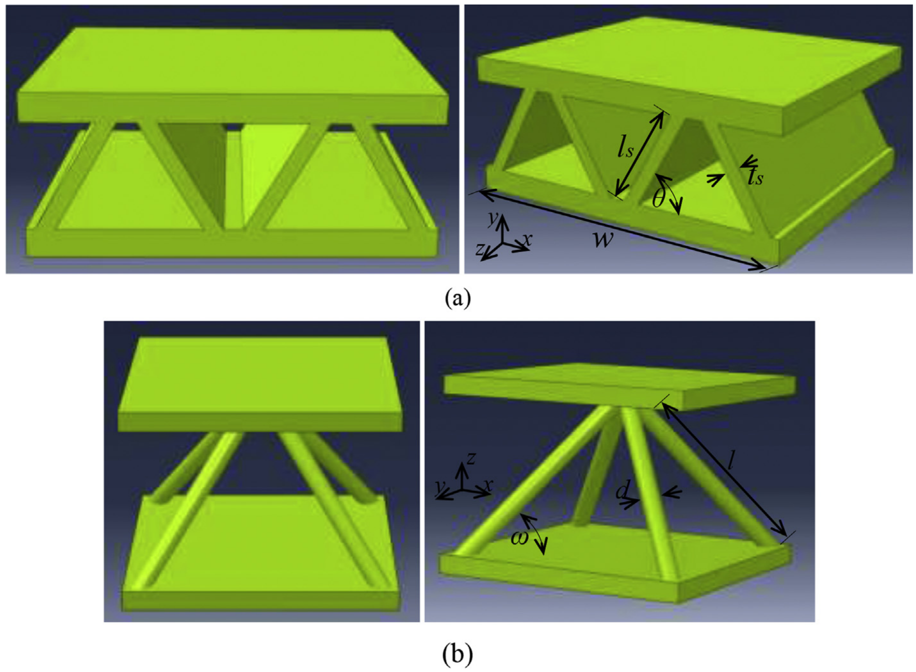


**Fig. 1.** Typical lattice truss material: (a) corrugated planar truss-core sandwich material and (b) 3D lattice truss core sandwich material.

for liquid Si at 1500 °C in vacuum. Dong et al. [12] fabricated Ti–6Al–4V octet-truss lattices, which exhibit excellent mechanical properties compared to other cellular material – cell topology combinations, and appear to be promising candidates for high temperature applications where a robust mechanical performance is required. Roper [13] proposed multi-objective optimization method to design multifunctional sandwich panel heat pipes with micro-architected truss cores. As the Young's modulus and the strength of the ceramics are temperature dependent [14–16], the mechanical behaviors of the high temperature lattice truss composites tightly relate to the temperature. As described by Liu et al. [17], strength of the fiber reinforced lattice truss material decreases when the temperature increases to 300 °C.

In this paper, temperature dependent behaviors of high temperature ceramic lattice truss materials were discussed and the corresponding high temperature failure criteria of the lattice truss ceramic matrix composite were proposed.

## 2. Temperature dependent theory of lattice material

Lattice truss material usually has two styles, as shown in Fig. 1. One is three-dimensional (3D) lattice truss material, such as the pyramidal lattice truss [8–10]. The other is planar lattice truss material, such as the corrugated lattice truss material [6,7].

### 2.1. Temperature dependent Young's modulus

Temperature dependent Young's modulus was suggested by Wachtman et al. [18] as

$$E = E_0 - BT\exp(-T_0/T), \tag{1}$$

where $E_0$ is the value of $E$ at $T = 0K$, and $B$ and $T_0$ are constants. Baranovet al. [19] modified the model and Li et al. [14] suggested a more complex model. Equation (1) has been approved to be effective to fit test results and was adopted in this paper to describe the temperature dependent Young's modulus of $HfB_2$ suggested by Wuchina et al. [20], as shown in Fig. 2(a). The fit curve is expressed by

$$E = 445 - 0.6T\exp(-2300/T). \tag{2}$$

### 2.2. Temperature dependent strength

Strength of the ceramics, $\sigma_Y(T)$, under high temperature usually decreases with the temperature. Commonly,

$$\sigma_Y(T) = \begin{cases} \sigma_{th} - k_1 T & T < T_1 \\ \sigma_{th} - k_1 T_1 - k_2(T - T_1) & T \geq T_1 \end{cases}. \tag{3}$$

where $\sigma_{th}$ is the strength at $T = 0$ K. $k_1$ and $k_2$ are constants, denoting the slope of strength variation. As shown in Fig. 2(b), two simple relations of temperature dependent strength of $HfB_2$ [20] were fitted by

$$\sigma_Y(T) = \sigma_{th} \tag{4}$$

for Gen A with $\sigma_{th} = 335$ MPa and

$$\sigma_Y(T) = \sigma_{th} - kT. \tag{5}$$

for Gen B with $\sigma_{th} = 455$ MPa and $k = 1/6$.

### 2.3. Temperature dependent behaviors of struts

Strength of the strut is given by

$$\sigma_T(T) = \sigma_Y(T) \tag{6}$$

in tension and

$$\sigma_C(T) = \begin{cases} \sigma_Y(T) & \text{for fracture} \\ \sigma_B(T) = \mu\dfrac{\pi^2 E(T) I}{l^2 A} & \text{for buckling} \end{cases}, \tag{7}$$

in compression, where $\sigma_T$ and $\sigma_C$ denote the strength in tension and compression, respectively. $\mu$ is the constraint coefficient. $I$, $A$ and $l$