FINITE ELEMENT SIMULATION OF SHOCK ENHANCEMENT IN CELLULAR STRUCTURES UNDER IMPACT LOADING

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Abstract

In recent years, the strength enhancement of cellular structures under impact loading has been found by some scientists during experiments. But the influence of the impact velocity and relative density of the materials on the shock enhancement was seldom studied. In this paper, the impact response of aluminium foam and its dependence on relative density and impact velocity are analyzed using Finite Element Method (FEM). The simulation results show that under large impact velocity, the elastic wave as the pioneer goes through the whole sample and makes the sample equilibrating. When the stress exceeds the plateau stress of the material and makes it densified, the shock wave will be generated and lead to stress unequal at the two ends of the specimen within a certain period. Shock enhancement of the cellular structure becomes more significant with lower relative density and high impact velocity. The estimated shock front velocity increases with both impact velocity and relative density.

1 General Introduction

Cellular solids such as honeycomb and foam have been widely used in systems for protection from impacts, sandwich panels for lightweight structure, acoustical wave attenuation and heat sinks for electronic devices [1]. Such applications require knowledge of cellular material properties, especially their compressive mechanical response at impact loading. The mechanical behavior of aluminum foams were also studied at the strain rate ranging from 10^{-3}-10^{3} 1/s [2-4]. In recent years, the strength enhancement of cellular structures under impact loading was found by some scientists during experiments. For the first time, Elnasri et al successfully observed the shock front in experiments using a high speed camera and the mechanism of shock enhancement was simply explained [5, 6]. However, the relationship among shock enhancement, relative density of material and applied impact velocity is rarely analyzed.

In this paper, the impact response of an aluminium foam was simulated via finite element method (FEM). Based on the FEM simulation results, the influence of relative density and impact velocity on the shock enhancement of the material was analyzed carefully.

2 Finite Element Simulation

ABAQUS explicit finite element code was used to perform the simulation. The FEM model employed in this paper consisted three parts: the strike bar, the specimen and the pressure bar. Both the strike and pressure bar were elastic aluminium bars with diameter of 60mm, length of 6000mm, elastic modulus of 70GPa and the Poisson's ratio of 0.3. The specimen was regarded as continuous solid with diameter of 40mm and thickness of 40mm (Fig. 1). Although the data on the uniaxial compression behaviour of aluminium foam can be found from literatures, rare results were focused on the mechanical behaviour of the same material with different relative density. To consider the influence of relative density on the impact response, the parameters of a simple rate-nonsensitive constitutive model proposed by Gibson and Ashby [1] was firstly calculated based on the limited experimental results from literatures. Then the uniaxial compression behaviour of aluminium foam with four kinds of relative densities was predicted using the Gibson-Ashby model. Based on these predicted data, the influence of relative density on the impact response was analyzed via FEM. During simulation, each density of aluminium foam was suffered from three different velocities of impact load ((see in Tab. 1). The Poisson's ratio of the foam was taken as 0. As it has been proved by many researchers that open cell aluminum foam is rate insensitive, we consider that the stress-strain relation in this simulation is independent on applied strain rate. We applied a surface-to-surface contact between the specimen and the strike and pressure bars with a friction coefficient of 0.01.

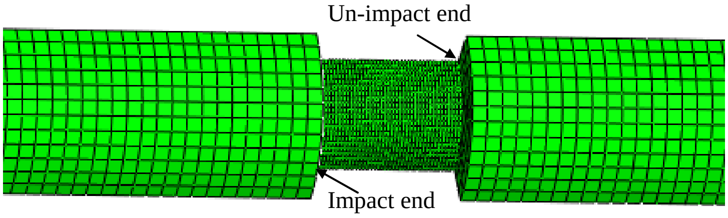

Fig.1 Finite element model

Table 1 Summary of simulated conditions

Relative density	0.05			0.11			0.15			0.21		
Impact velocity (m/s)	20	25	30	30	40	50	30	40	50	30	40	50

To analyze the influence of relative density and impact velocity on the shock enhancement, relative density of the foam was set as 0.05, 0.11, 0.15 and 0.21 respectively. During simulation, each density of the specimen underwent three different impact velocities (see in Tab. 1). Then the influence of impact velocity on the shock enhancement was also investigated. To save computational time, only quarter of the whole model was employed into FEM simulation and the corresponding symmetrical boundary conditions were applied.

3 Results and Discussions

Fig. 2 shows the stress history of the two ends of the specimen. It can be seen that at the beginning of impact, deformation occurs firstly at the impact end of the specimen and propagates through the specimen towards the un-impact one (see in Fig.1). As impact end of the specimen suffers elastic deformation at the beginning of deformation, elastic stress wave forms at the impact end and propagates as a prior wave through the specimen. When the elastic prior wave arrives at the un-impact end of the specimen, the whole specimen will be in elastic deformation. The propagation of the elastic prior wave from one end to another will result in a delay of the beginning of the stress history curve on the un-impact end (shown in Fig.2). As soon as the stress at the impact end of the specimen reaches the plateau stress σ_{pl}, local densification due to plastic collapse firstly occurs there and propagates towards the un-impact end. It should be noticed that after the long plateau phase, stress will increase sharply as deformation increase, and leads to the concave part of the stress-strain curve. According to the theory of stress wave, shock wave forms in the concave part of stress-strain curve. That means if the impact velocity is high enough, local densification will occur firstly at the impact end of specimen. As a result, stress at impact end will increase sharply and propagate as a shock wave through the specimen towards its un-impact end. At the point the shock front passing through, stress will increase sharply while material ahead of the shock front is still in the platform deformation stage.

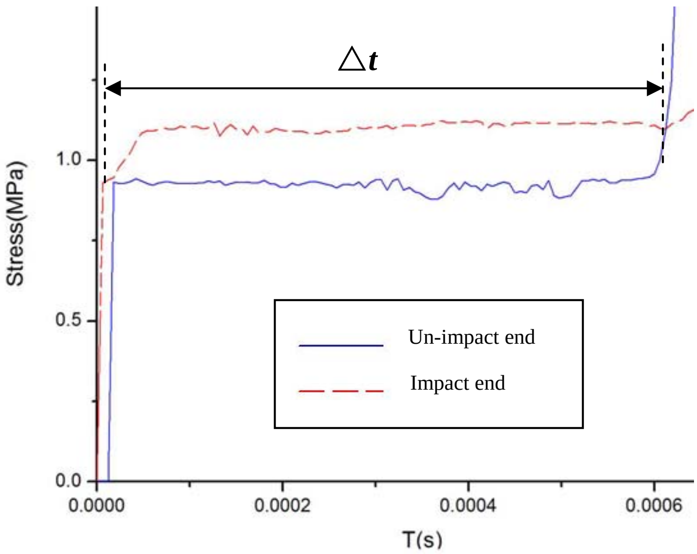

Fig.2 Stress history ahead of and behind the shock front

Table 2 Summary of simulation results

Relative density	*Impact velocity (m/s)*	*Stress at impact end (MPa)*	*Stress at un-impacted end (MPa)*	*Stress discrepancy between two ends (%)*	*Shock front velocity U (m/s)*
0.05	20	1.03	0.92	12	53.5
	25	1.1	0.93	18.3	62.3
	30	1.16	0.93	25	70.4
0.11	30	4.9	4.4	11.4	80
	40	5.4	4.45	21.3	97.4
	50	5.8	4.46	30	115
0.15	30	8.9	8.2	8.5	84.4
	40	9.34	8.2	14.6	102.7
	50	10	8.2	22	119
0.21	30	16.7	16	4.3	87.2
	40	17.6	16	10.1	108
	50	18.5	16	15.6	127

If the shock front velocity U can be defined as:

$$U \approx l_0 / \Delta t \qquad (1)$$

where l_0 is the original length of the specimen, $\triangle t$ is the time delay corresponds to the period that the shock front propagates from the impact end to its un-impact end. Then the velocity of shock front can be estimated quantificationally (see in Tab. 2).

The stress at impact and un-impact ends of the specimen, stress discrepancy between two ends of the specimen, shock front velocity and critical impact velocity for each simulated condition are listed in Tab.2. It can be found that for the specimen with the same relative density, stress at impact end increases with impact velocity while that at un-impacted end remains almostly the same. As a result, stress discrepancy between two ends of the specimen increases when impact velocity increases. At the same time, the estimated shock front velocity of the foam with the same relative density increases with impact velocity. For the same impact velocity, the stress at both ends of the specimen increases with increasing relative density while the stress discrepancy between two ends of the specimen decreases. It can also be seen in Tab.2 that the estimated shock front velocity increases with increasing relative density when the impact velocity remains the same. This means that the relative density of foams is also an important factor for shock enhancement effect at impact loading.

4. Conclusions

From above discussion, the key points can be drawn as the followings: (1) Under impact loading, elastic stress wave forms firstly at the impact end and propagates as a prior wave through the specimen towards the un-impact end. Shock front can be observed when the stress at impact end exceeds the plateau stress. The shock front will lead to stress unequal at the two ends of specimen within a long period. (2) Shock enhancement of the cellular structure is dependent on both relative density and impact velocity. The estimated shock front velocity increases with both impact velocity and relative density of material.

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