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Investigation of copper lattice structures using a Split Hopkinson Pressure Bar

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The paper deals with experiments on 3D printed lattices in a Split Hopkinson Pressure Bar. An energy-based evaluation of the measured wave signals enables us to compare the damping properties of two different copper lattice structures.

1 Introduction

The ability to model a wide variety of structures through 3D printing processes is a relatively new field, which is highly important for many disciplines. The response of such structures on mechanical or thermal loadings is therefore of great interest. This paper presents experiments on high strain-rate loading of printed copper lattices performed with a Split Hopkinson Pressure Bar (SHPB).

Typically, the SHPB is used to determine elastic and plastic material properties, and a cylindrical probe made of homogenous material works as a specimen. The conventional evaluation of the SHPB experiment presumes a uniform state of stress in the specimen. Therefore samples with a micro-structure are only suitable to a limited extent for determining material properties since the waves do not move through the specimen's body over a homogeneous cross-section.

With the aim to understand the energy absorption of 3D-printed structures under impact, we chose here an energy-based evaluation of the measured signals. Our SHPB device uses aluminum material for the striker, the incident, and the transmission bar. The bars have a diameter of 20 mm and a length of 1800 mm. Strain gauges are applied in the center of each bar, which allows us to record the propagating pulses. Further details on our setup can be found in [1, 2].

2 Copper lattice structures

We investigate two types of 3D-printed lattice structures. They have an octet-truss and a F2CCZ lattice as unit-cells; both show different nodal connectivity. The truss diameter and the length of the unit cell are 200 µm and 1 mm, respectively. Each lattice structure has $5 \times 5 \times 5$ unit-cell repetitions. For the fabrication of specimens, a system with infra-red laser source was used. The material was pure Cu-ETP powder with diameter of 16-63 µm. Laser power, scan speed, and layer height are 600 W, 800 mm/s, and 30 µm, respectively. We used a contour scanning strategy, and the beam compensation was 70 µm. The fabricated lattices are cube-shaped with a length of 5 mm, as shown in Fig. 1.

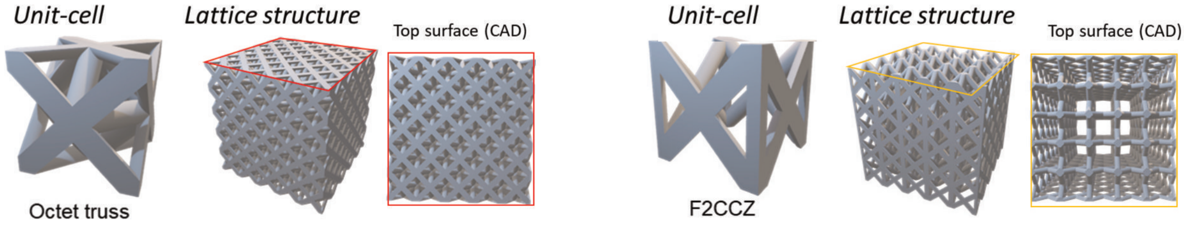

Fig. 1: Two copper lattice structures: octet truss (left) and F2CCZ truss (right)

3 Energy of specimen deformation in the SHPB

The elastic energy of a pulse in a bar can be determined as

$$W = \int_V w^e \mathrm{d}V = A\, c\, t_0 \int_0^{\epsilon} \sigma(\tilde{\epsilon})\, \mathrm{d}\tilde{\epsilon} \qquad \text{with} \qquad t_0 = 2\,\frac{l_{\text{Striker}}}{c} \tag{1}$$

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where V, A and c are the volume, the cross section area and the elastic wave speed of the bar, respectively. The duration of the pulse is t_0 and determined by the length of the striker in a SHPB. Assuming a rectangular strain pulse and an elastic behavior of the bar, $\sigma = E\,\epsilon$, we obtain for a constant Young's modulus E after integration: $W(\epsilon) = {}^1\!/_2 E A\, c\, t_0 \epsilon^2$. In the SHPB experiment three waves are measured: the incident (I), the reflected (R) and the transmitted strain pulse (T). For each of these pulses corresponding energy can be calculated:

$$W_I = \frac{1}{2} E\,A\,c\,t_0\,{\epsilon_I}^2 \qquad W_R = \frac{1}{2} E\,A\,c\,t_0\,{\epsilon_R}^2 \qquad W_T = \frac{1}{2} E\,A\,c\,t_0\,{\epsilon_T}^2 \tag{2}$$

For a system of two bars without a specimen, the energy balance holds that: $W_I = W_R + W_T$. When a specimen is sandwiched between the bars, an energy difference is measured. This energy difference can be calculated accordingly, $\Delta W = W_I - W_R - W_T$. We assume the specimen to be small and in stress equilibrium [3], i. e.,

$$\epsilon_T = \epsilon_I + \epsilon_R \tag{3}$$

and after evaluation of these expressions, we obtain the energy difference:

$$\Delta W = E\,A\,c\,t_0\,(\epsilon_I + \epsilon_R)\,(\epsilon_I - \epsilon_T)\ . \tag{4}$$

This energy is stored in the specimen and can considered to be the damping of the propagating wave. Depending on the specific material used, this energy can be converted into elastic, viscoelastic or elastic-plastic deformation.

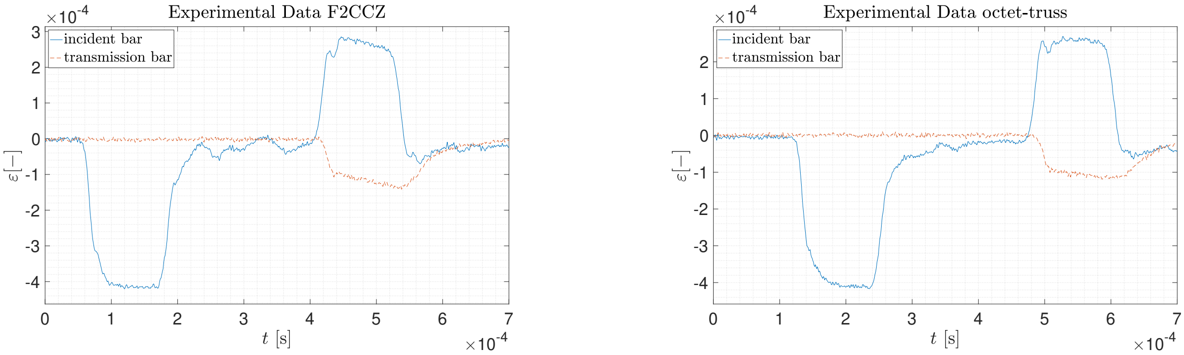

Fig. 2: Wave signals measured from strain gauges of the SHPB with a striker length of 300 mm and a velocity of 3.3 m/s

4 Results and conclusion

From the measured incident, reflected, and transmitted signals of the SHPB, we calculated the relative energy difference for the two different copper lattice structures as

$$\frac{\Delta W}{W_I}\,(\text{F2CCZ}) = 0.218 \quad \text{and} \quad \frac{\Delta W}{W_I}\,(\text{octet-truss}) = 0.229\,. \tag{5}$$

The stored energy of two lattice structures differs because of their different deformation mechanisms. The octet-truss lattice has higher nodal connectivity than the F2CCZ and so the deformation is mostly stretch-dominated [4]. Apart from that, the F2CCZ lattice has relatively low nodal connectivity, and the nodal bending or shear lowers the compressive strength of the structure. Therefore, an octet-truss structure requires more energy to deform than a F2CCZ structure. Our SHPB results confirm this general observation.

This short study demonstrates that specimens with internal structure can be characterized and that the energy-based SHPB approach can be applied to 3D architectured material to evaluate the energy or shock absorption efficiency.

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