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Analysis of 3D metallic auxetic structures at high rates of strain using finite element DIC

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Introduction

Auxetic 3D-printed metamaterials are structures that exhibit a well defined negative Poisson's ratio. Structures with auxetic properties show interesting behaviour in comparison to conventional non-auxetic metamaterials when loaded with a high rate of strain. This makes the materials an interesting candidate for application in the automotive sector, especially in crash applications. The structural response of auxetic structures is dependent on loading rate. At quasi-static conditions, auxetic structures generally exhibit well defined negative Poisson's ratio over a wide range of strains. However, at dynamic rates of strain, this is not necessarily the case: the magnitude of the rate of strain determines whether an auxetic effect occurs or the structure collapses. If the structure does not have enough time to achieve dynamic equilibrium, it experiences structural failure similar to pore collapse in foams before auxetic behaviour can occur, see *Figure 1*. To provide an in-depth understanding of a structure and collect data in order to accurately model and simulate the metamaterial, a detailed analysis of the structural response is mandatory. Our work investigates an alternative approach for obtaining accurate deformation data for auxetic structures under dynamic loading.

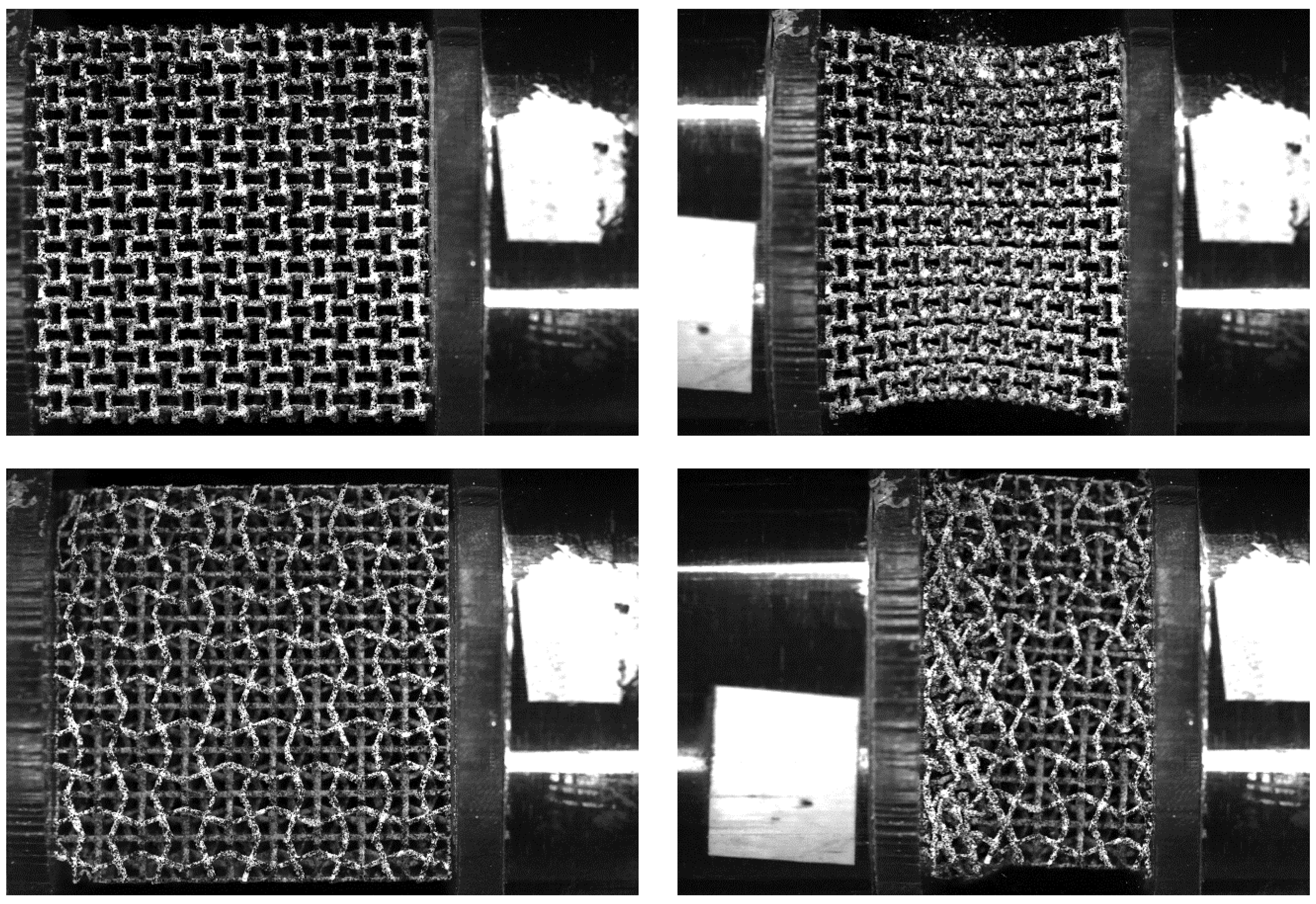

Figure 1: Two 3D structures, printed using EOS Maraging Steel MS1, in their initial state (left) and the loaded state (right) using a Symmetric Direct Impact Hopkinson Bar with a strain rate of 370 s^{-1}. The structure on top exhibits pronounced auxetic behaviour, while the other structure experiences structural failure similar to pore collapse in foams.

Digital Image Correlation

The analysis of a specimen is often performed using Digital Image Correlation (DIC). DIC registers two or more images of the same scene and extracts a displacement field. Advanced DIC codes add additional information, such as residuals and noise sensitivity [1].
To calculate the displacement field, two image frames *f* and *g* at each pixel position *x* shot at two different instances in time are assumed. The image frames are matrices with each elementary component representing a grey level value. Assuming the displacement *u(x)*, the images can be related as

$$f(x) = g[x + u(x)]$$

corresponding to grey level conservation. The image is divided in smaller sub-images (or elements, facets). The displacement field *u(x)* is then calculated by minimizing the mean squared deviation of both images over a sub-image:

$$\mathrm{T}(u_p) = \int_{sub-image} \left[f(x) - g\left(x + \sum u_p \psi_p(x) \right) \right]^2 dx$$

approximating the displacement field using a field function $\psi_p(x)$ and the unknown degrees of freedom u_p.

$$u(x) = \sum u_p \psi_p(x)$$

Local and global DIC are distinguished. In case of local DIC, the displacement field of adjacent sub-images are computed independently from each other. This process can be well parallelized, is robust and computationally effective. For these reasons, local DIC often implemented in commercial codes. However, local DIC results in displacement fields with jump discontinuities, requiring spatial smoothing.
When applied to slender structures such as auxetic lattices, local DIC often yields inaccurate measurements. These structures include empty spaces, where the displacement is known to be zero. However, spatial smoothing interpolates this information into the solution for the displacement of the lattice members, thus causing an underestimate of the true displacement. Therefore, typical commercial tools tend to reach their limits when it comes to its application on auxetic structures.
In contrast, global DIC employs continuous basis functions which enforce connectivity of the sub-images. The resulting displacement of adjacent elements is continuous, requiring no spatial smoothing. Therefore, the global DIC displacement field does not erroneously underestimate the true displacement, if the sub-images are chosen correctly, i.e., without empty areas.

Finite Element DIC

The continuity is important for relating the experiments with a finite element simulation. Since the pictures already have to be divided in sub-images, it is natural to consider a structure directly compareable to FE simulations for identification and validation. The pictures are based on pixels, so it is logical to use requtangular or triangular elements to create a mesh. Since we do not want to calculate the displacement of empty areas, the mesh is created based on the CAD model of the structure, see *Figure 2*. This method results in a displacement field, which deforms depending on the deformation of the structure. The structure can be analyzed locally in detail. Beyond the displacement, the displacement field can be used to calculate strains, rotations and other information, which contributes to an in-depth understanding of the structure and its auxetic response.

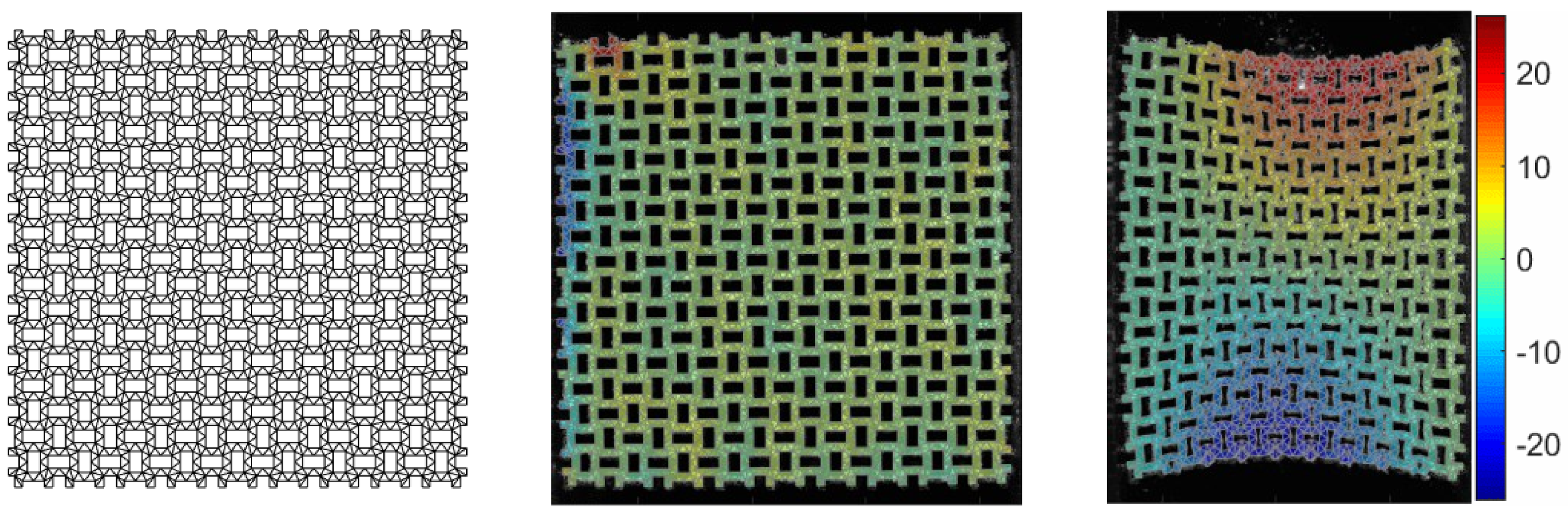

Figure 2: On the left is the FE mesh based on the CAD model of the structure. In the middle, the mesh is applied to the surface of the structure in its initial state. On the right, the structure has already been deformed using a Symmetric Direct Impact Hopkinson Bar with a strain rate of 370 s^{-1} showing the perpendicular displacement in pixels.

Conclusion and outlook

The method of global DIC combined with a finite element mesh yields accurate results for structural deformation and information which is useful in developing new material models. The next step is the implementation of the results in a numerical simulation. The simulation based on this information can be used to find a critical strain rate where the structural response devolves from auxetic to collapsing. Additionally, the information obtained through the DIC can be used to find homogenized material models and therefore improve calculation times of the simulations.

References

[1] F.Hild and S.Roux. 2012. Digital Image Correlation. Optical Methods for Solid Mechanics. A Full Field Approach, pp.183-228.