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Titanium lattice-cored short beams: in-plane flexural behaviour numerical simulation

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Abstract

To enhance the mechanical performance and lightweight design of structural components, such as those found in automobiles, researchers have explored innovative sandwich structures incorporating metallic lattice cores. These lattice cores offer exceptional strength-to-weight ratios, making them ideal for applications demanding high performance and minimal mass. Although out-of-plane loading scenarios are well-studied, less focus has been given to in-plane flexural stress, which is common in automotive frames.

In this study, a finite element method (FEM) model was employed to investigate the in-plane flexural behaviour of a titanium lattice-cored short beam. The beam was fabricated using EB-PBF (Electron Beam Powder Bed Fusion), an additive manufacturing technique capable of producing complex shape parts but susceptible to introducing defects that can compromise mechanical properties.

A comprehensive comparison between the FEM model results and experimental data revealed a strong correlation, validating the accuracy of the simulation. This study provides valuable insights into the in-plane flexural response of lattice-cored structures and highlights the importance of considering damage mechanisms in additive manufacturing processes.

Keywords: Numerical modelling; In-plane bending; Lattice structures; Titanium; Additive manufacturing.

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1. Introduction

The increasing demand for lightweight and high-performance materials in various industries, particularly in the automotive sector, has driven significant research efforts into developing innovative structural components (Hassan and Saeed (2024), Maskery et al. (2016)). Among the promising solutions, sandwich structures with metallic lattice cores have emerged as a compelling option due to their exceptional specific strength and stiffness (Sahu et al. (2022), Bellini et al. (2021a)). In fact, as assessed by Bellini et al. (2021b), high specific mechanical properties can be attained by considering the cellular form instead of the bulk one. These structures consist of two face sheets, typically made of a dense material, sandwiching a cellular core composed of a periodic arrangement of interconnected struts. The lattice core imparts significant stiffness and energy absorption capabilities to the sandwich panel, making it well-suited for applications requiring high load-bearing capacity and impact resistance (Taghipoor et al. (2020), Bellini et al. (2021)).

Numerical models have been proposed to analyse the mechanical behaviour of lattice structures in the past. Cantaboni et al. (2024) used numerical simulation to predict the mechanical characteristics of such structures, finding a discrepancy with experimental results due to geometrical unconformities. The same authors investigated the influence of cell type and building orientation on compressive behaviour (Cantaboni et al. (2022)). Carraturo et al. (2021) employed a numerical model that took into account the real geometry of a cell to enhance the prediction accuracy. In their model, Takano et al. (2017) considered the presence of material imperfections previously evaluated through computer tomography. Arrieta et al. (2018) proposed a numerical model based on the mechanical properties of struts produced along different building orientations. Taghipoor and Nouri (2019) employed a numerical model to investigate the influence of the geometrical parameters of the lattice structure on its mechanical properties. Liu et al. (2017) proposed a model to simulate lattice structures with defects by testing specimens produced with induced imperfections. Di Caprio et al. (2022) adopted a model based on shell and beam elements to simulate lattice structures, considering the structure weight to calibrate it.

While the out-of-plane bending behaviour of lattice-cored sandwich structures has been extensively studied, the in-plane flexural response remains relatively unexplored. This is particularly relevant for automotive applications where components are subjected to complex loading conditions, including in-plane bending moments. Understanding the in-plane flexural behaviour of these structures is essential for their optimal design and utilisation.

Furthermore, the advent of additive manufacturing technologies, such as EB-PBF (Electron Beam Powder Bed Fusion), has revolutionised the fabrication of complex geometries and enabled the production of lattice-cored structures with tailored properties (Dong et al. (2017), Epasto et al. (2019), Mahbod and Asgari (2019)). However, the additive manufacturing process can introduce defects into the final product, potentially affecting the mechanical performance of the component (Echeta et al. (2020), Del Guercio et al. (2020), Bellini et al. (2024, 2023)).

This study aims to investigate the in-plane flexural behaviour of titanium lattice-cored short beams fabricated using EB-PBF. The specific objectives of this research are:

- To develop a finite element model to accurately simulate the in-plane flexural response of the lattice-cored beam.
- To experimentally validate the numerical model by comparing the predicted failure loads and deformation patterns with experimental results.
- To assess the influence of defects introduced by the EB-PBF process on the mechanical performance of the lattice-cored beam.

By achieving these objectives, this research will contribute to the fundamental understanding of the in-plane flexural behaviour of lattice-cored structures and provide valuable insights for the design and optimisation of such components in engineering applications.

2. Material and methods

The test specimen consisted of a lattice core with a rectangular cross-section of 10 mm by 9 mm and a length of 30 mm. The core was encased in a skin with a thickness of 1 mm. The lattice architecture was comprised of an octet-truss unit cell. This type of cell is a centred face cubic (CFC) structure consisting of 24 struts, with an octahedron inside, composed by 12 struts. The cell side length was 6 mm, and the beam diameter was 1 mm. It is important to note that these dimensions are nominal. The material used to fabricate the specimen was the Ti6Al4V titanium alloy, a common material in aerospace applications.

The three-point bending test was employed to characterise the mechanical response of the specimen. In this test configuration, the specimen was positioned on two horizontal supports and loaded in the centre by a vertical loading nose. While this test is typically used to evaluate the out-of-plane properties of sandwich structures, the current study focused on the in-plane characteristics. Therefore, the load was applied perpendicularly to the direction of the skins, as illustrated in Fig. 1. The span length between the supports was set to 20 mm, and the loading speed was set to 2 mm/min.

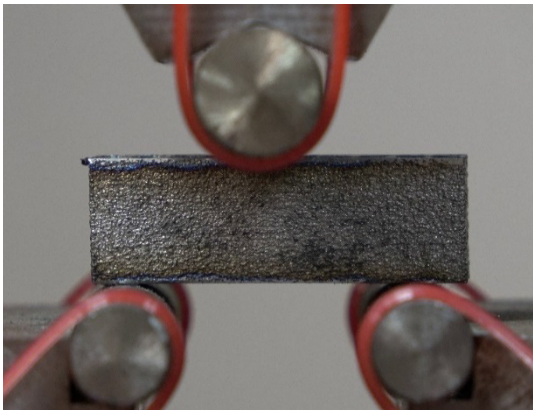

Fig. 1. In-plane three-point bending test of a short beam.

As concerns the numerical model, the entire FE model was made of shell and beam elements to enhance computational efficiency. In particular, 1364 beam elements were used to discretise the lattice core, while 1344 shell elements were necessary to simulate the skins. The diameter of the former was 0.8 mm, instead of 1 mm, as indicated by the design, while the skin thickness was 0.8 mm instead of 1 mm. In fact, the produced specimens were weighed and resulted lighter than evaluated from the nominal CAD model, denoting a thinning of the trusses and skins induced by the process. Therefore, the diameter of the trusses and the thickness of the skins were reduced by the amount required so that the weight of the virtual model matched the experimentally measured one. The load application was simulated by adding a rigid cylinder to the specimen centre and then assigning a motion law to the cylinder. The same approach was adopted for the supports, but in this case the cylinders were blocked in the space. As visible in Fig. 2, defining a contact between the specimen and the cylinders was necessary. The contact used in the latter case was the sliding one, which hindered the penetration between the parts in contact but allowed the relative tangential displacements.

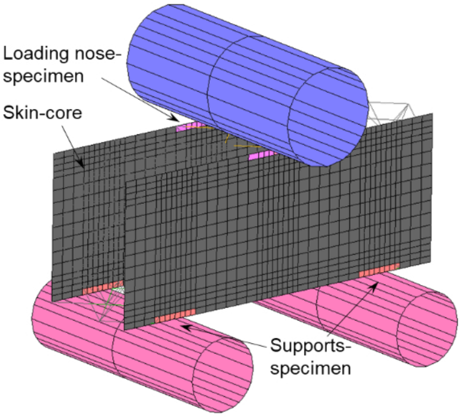

Fig. 2. Mesh adopted for the numerical model.

3. Results

The load-displacement curve obtained from the numerical simulation is reported in Fig. 3 and compared with that obtained from the three-point bending test. As it can be noted from the graph, both numerical and experimental results presented a similar trend, that was characterised by a first linear elastic part followed by a second part, that was pseudolinear. In this part, plastic deformation arose, and the loading path ended with the failure of the specimen. It is worth noting that the model was able to predict the maximum attained load quite well. In contrast, the predicted stiffness, that is the slope of the first linear part, was a bit overestimated, as well as the transition from the linear to the pseudo-linear zone. For this latter parameter, the discrepancy was less than 7%. The actual specimen presented a residual strength after the primary failure, while it was not possible to simulate this behaviour with the adopted model.

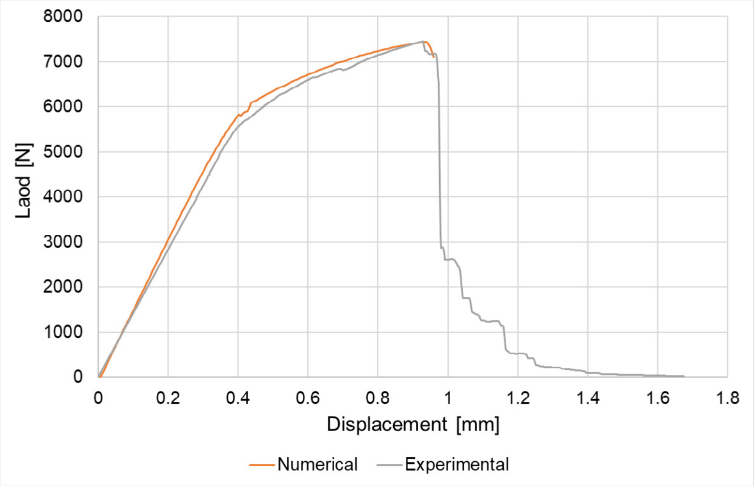

Fig. 3. Load-displacement curves: comparison between numerical results and experimental test.

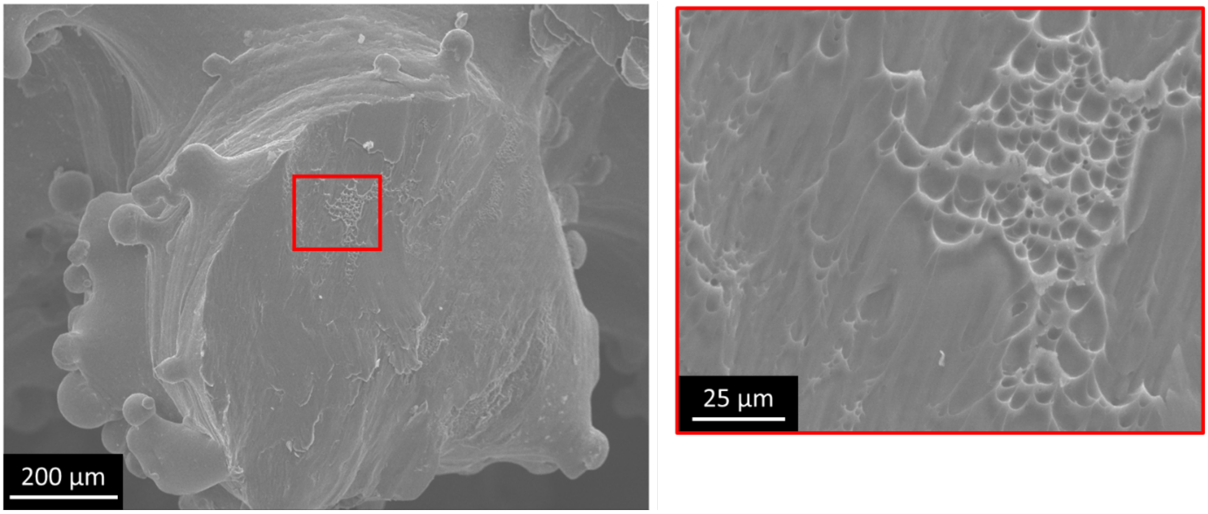

Fig. 4. SEM micrograph of a truss fracture surface.

Image analysis of SEM micrographs was carried out, too, in order to identify the damage mechanism better. In Fig. 4, the fracture surface of a beam of the lattice is reported, and, on the right, there is the magnification of a part of that surface. There is the presence of some dimples, that denote the ductile behaviour of the material. The dimples are clearly stretched along a direction that is not perpendicular to the surface, indicating the presence of shear stress, probably due to the reduced length of the beam. Moreover, the roughness of the lateral surface of the beam is very high, and the presence of unmelted or partially melted powder particles can be noted. These particles increase the weight and the thickness of the beam, but their contribution in terms of mechanical properties is very low. This explains the need to consider a thinner geometry for the simulation of the mechanical behaviour of such specimens.

4. Conclusions

In this work, a numerical model for predicting the flexural behaviour of lattice-cored short-beam specimens was proposed and validated. In particular, the in-plane bending was considered, a loading configuration scarcely analysed in the literature. Experimental three-point bending tests were carried out on the samples, that were manufactured through electron beam melting technology. The load-displacement curve calculated by the numerical model adequately represented that found by the experimental runs. In fact, the maximum load was predicted very well, while the rigidity of the specimens was slightly overestimated. Micrographs were taken by SEM, and the ductile failure was identified. The dimples direction was not orthogonal to the fracture surface, denoting the presence of shear stresses.

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