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CHARACTERIZING MICROSTRUCTURAL DAMAGE IN CEMENTITIOUS COMPOSITES REINFORCED WITH 3D-PRINTED AUXETIC LATTICES USING X-RAY COMPUTED TOMOGRAPHY

ZHAOZHENG MENG[*] AND BRANKO ŠAVIJA [*]

[*] Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
e-mail: z.meng@tudelft.nl and b.savija@tudelft.nl

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Abstract: Cementitious materials are limited by its brittle nature, leading to the adoption of steel bars or fibers as reinforcement to improve ductility. With advances in additive manufacturing, 3D-printed lattice structures have emerged as a promising alternative for reinforcing cementitious composites, enabling enhanced mechanical properties This study explores the incorporation of a three-dimensional lattice structure with negative Poisson's ratios (auxetic behavior) into cementitious composites. Uniaxial compression test showed that the densification energy could reach 170% times of reference cement mortar. Because of the lateral contraction tendency of auxetic lattices which would constrain the expansion of cementitious matrix, the peak strength for auxetic lattice reinforced cementitious composites was 1.4 times of their non-auxetic counterparts. To further disclose the interaction mechanisms between the 3D-printed lattice and the cementitious matrix, X-Ray computed tomography (X-ray CT) was utilized to analyze the internal damage under varying strain levels. Micro-CT characterization revealed distinct failure mechanisms for auxetic and non-auxetic lattice reinforced cementitious composites. Due to a larger lateral expansion tendency of the non-auxetic lattice structure, interfacial shear cracking was observed between the lattice reinforcement and cementitious matrix. In contrast, the opposing deformation pattern of auxetic lattices resulted in fewer cracks in the core area, more even stress distribution, and prevention of large crack formation, thus enhancing the composite's energy absorption capacity. Moreover, quantitative analysis from CT scans showed that the crack volume in the core of the auxetic lattice-reinforced composites was almost 60% lower than that of the non-auxetic samples at 2.5% strain. At 5% strain, the auxetic lattice continued to limit crack merging, but at 7.5% strain, although the total crack volume remained 20% lower, the ability to prevent crack coalescence diminished. These insights from micro-crack analysis provide valuable guidance for designing cementitious composites reinforced with auxetic lattice structures.

1 INTRODUCTION

Concrete, as the most widely used construction material, is inherently brittle. It is therefore traditionally reinforced with steel bars to improve ductility. However, the role of steel bars as reinforcement is activated only after the appearance of cracks, and this passive reinforcement often activates too late, as the initial cracks will severely weaken the ductility to withstand repeated load or earthquake where ductility is required [1]. Therefore, researchers have explored the use of 3D-printed lattices with negative Poisson's ratios (also known as auxetic lattice) as an alternative to actively reinforce cement matrix prior to the cracking and lead to improved ductility of the cementitious composites [2, 3].

The auxetic lattice is designed with a counter-intuitive behaviour under loading: it contracts laterally under vertical compression, and expand laterally when stretched vertically [4]. It is hypothesized that, under compression, the auxetic lattice will deform in the opposite direction to the cementitious matrix, providing additional confinement to the matrix. This interaction is expected to delay the onset of cracking and enhance the overall ductility of the composite. Recently, extensive research has demonstrated that cementitious composites with two-dimensional auxetic lattices can enhance energy absorption capacity [5]. However, the out-of-plane deformation has been identified as a limiting factor for further improving ductility [6]. In contrast, three-dimensional auxetic structures, which exhibit auxetic behaviour in both in-plane and out-of-plane directions, have been studied and shown to provide equivalent or even superior reinforcement effects with lower volume requirements compared to their two-dimensional counterparts [7].

Although the mechanical behaviour of cementitious composites with auxetic lattices has been extensively studied, the interaction mechanisms between the lattices and the matrix remain insufficiently explored. This is largely due to challenges in capturing internal damage within the composite, and external surface layers often fail first because of inadequate reinforcement, making surface-based observation techniques less effective. To address this limitation, this study X-ray CT to analyse the internal damage mechanisms of cementitious composites reinforced with three-dimensional auxetic lattices under uniaxial compression, with a focus on crack distribution and propagation. Non-auxetic lattices were included for comparison to better understand the role of auxetic behaviour in constraining the cementitious matrix.

2 EXPERIMENTS

The design of both auxetic and non-auxetic lattices is shown in Figure 1. The volume was approximately 1480 mm^3, resulting to a 18.5% reinforcement ratio for cubic composite samples with a side length of 20 mm. The lattices were 3D printed using vat photopolymerization techniques. Loctite 3D IND405 High Elongation Resin was selected as the base material, which has a maximum elongation rate of 101 %, and peak strength of 45 MPa according to the manufacturer. Afterwards, the lattices were embedded into cement mortar during casting, followed by a 30s vibration to ensure a uniform distribution of matrix. Table 1 summarizes the mixture proportions of cement mortar. The samples were tested after 28-day standard curing.

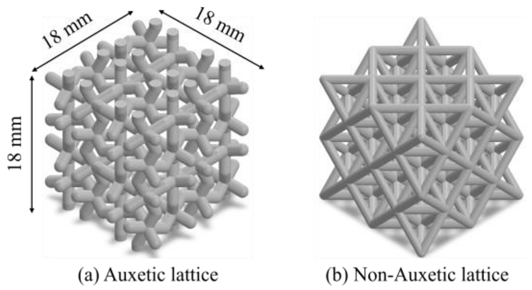

Figure 1: Geometry design of lattice structures.

Table 1: Mixture of cementitious matrix (g/L)

w/b ratio	CEM I 42.5 N	Fly ash	Sands	Water	Superplasticizer
0.4	615	728	616	538	2.6

Uniaxial compression tests were performed on both 3D printed lattice structures and cementitious composites. A loading rate of 0.01 mm/s was adopted, and the loading process was controlled by the LVDT mounted between two loading plate. Photographs were systematically captured at a five-second interval during the test to record the deformation states and calculate Poisson's ratios of the lattice structures.

For cementitious composites, CT scans were also conducted to observe the internal damage under compressive displacements of 0.5 mm, 1.0 mm and 1.5 mm, respectively. It should be noted that ex-situ CT scans were conducted in this study to reach different load levels, and the same sample was used during the scanning to maintain the consistency of the test. The CT scanning has a resolution of 15 microns. The CT images were reconstructed for subsequent quantitative and qualitative analysis. A crack segmentation procedure was conducted using Dragonfly visualization software. To enhance contrast, a top-hat filter was first applied to the original images. Cracks were then segmented based on gray value ranges, and only features with a volume larger than 0.1 mm³ were considered to eliminate potential misclassification of pores.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical properties of lattice structures

The uniaxial compressive stress–strain curves of auxetic and non-auxetic lattices are presented in Figure 2. For the auxetic lattice, the curves exhibited a continuous increase in stress, in contrast to the fluctuating pattern observed in the non-auxetic counterparts. This distinct behavior arises from the inward buckling of joints in the auxetic structure, which eventually come into joint contact, maintaining load-bearing capacity. In non-auxetic lattices, however, buckling did not result in new contacts, leading to fluctuating load-bearing performance until densification occurred. Despite these differences, no fractures were observed in either type of lattice, owing to the high elongation capacity of the printing base material.

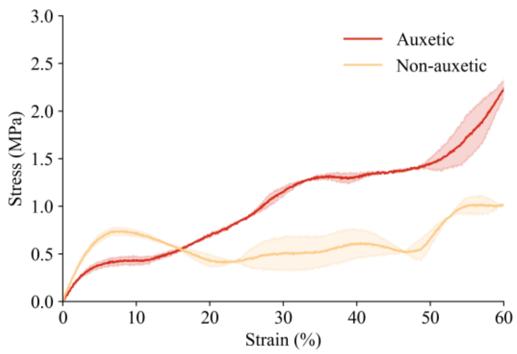

Figure 2: Compressive stress–strain curves of auxetic and non-auxetic lattice structures.

The Poisson's ratios of the 3D-printed lattices are presented in Figure 3. In this study, the Poisson's ratio is defined as the ratio of horizontal to vertical displacement of the lattice specimens, as measured by the camera. For the auxetic lattice, the Poisson's ratio started with a negative value but transitioned to positive during the densification phase due to contact between adjacent joints. In contrast, the Poisson's ratios of non-auxetic lattices remained approximately 0.3 after a strain of 10%.

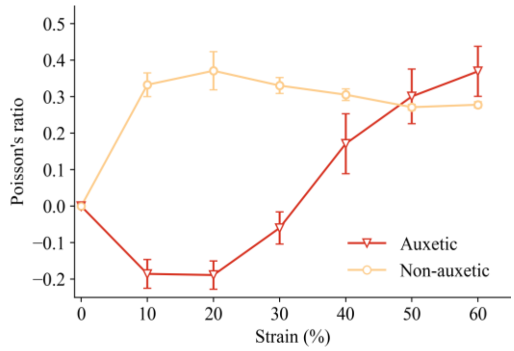

Figure 3: Poisson's ratios for auxetic and non-auxetic lattice structures.

3.2 Mechanical properties of cementitious composites

Figure 4 illustrates the compressive stress–strain curves of cementitious composites reinforced with auxetic and non-auxetic lattices. Unlike the non-auxetic structures, the auxetic lattice-reinforced composites exhibited a distinct stress peak before transitioning into a plateau stage, whereas the non-auxetic lattice-reinforced cementitious composites entered the plateau stage directly. This difference is likely due to the confinement effect of the auxetic lattice's negative Poisson's ratio, where lateral contraction constrains the cementitious matrix's lateral expansion, leading to increased stress. However, as compressive strain increases, this confinement effect diminishes due to the lower stiffness of the auxetic lattices compared to the cement matrix.

Although auxetic lattice yielded higher strength than non-auxetic counterparts, the strength of cementitious composites with lattice structures remained lower than that of the reference cement mortar. This is mainly attributed to the incorporation of softer polymer-based lattices into the matrix. Nevertheless, the post-peak ductility of the cementitious composites with 3D-printed lattice structures was significantly enhanced, making them promising for applications where energy absorption or impact resistance is needed.

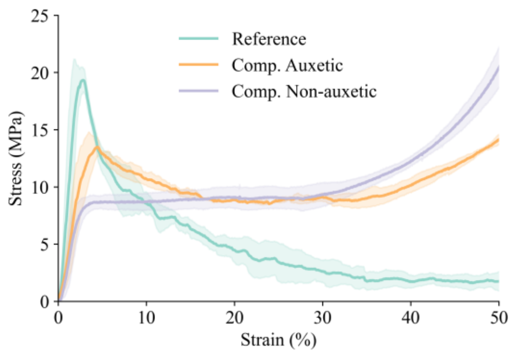

Figure 4: Compressive stress–strain curves of cementitious composites and reference mortar.

The densification energies for cementitious composites reinforced with auxetic lattice, non-auxetic lattice, and reference cement mortar are shown in Figure 5. The densification energy is defined as the energy absorption before reaching densification stage, and the detailed determination procedure for the densification stage can be found in literature [8]. The auxetic lattice demonstrated the most obvious improvement in densification energy for cementitious composites. While the non-auxetic lattice also increased densification energy compared to the reference, its average values were lower than those achieved with the auxetic structure. This difference can be attributed to the stress peak observed in composites reinforced with auxetic lattices, in contrast to the direct transition to the plateau stage seen in composites with non-auxetic lattices.

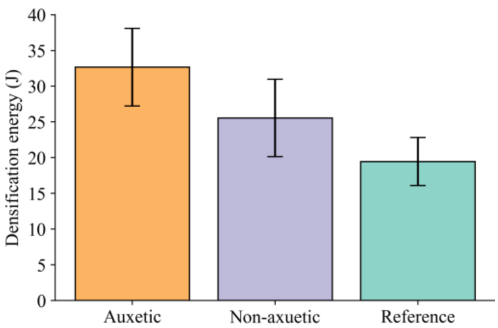

Figure 5: Comparisons of densification energy.

4 MICROMECHANICAL DAMAGE ANALYSIS

4.1 Crack volume

The micromechanical damage analysis was conducted based on the CT scanning results. Two cementitious samples embedded with auxetic and non-auxetic lattices were prepared and subjected to strain levels of 2.5%, 5%, and 7.5%, respectively. After reaching each strain level, the specimens were unloaded and analyzed using CT scanning. The total crack volumes, shown in Figure 6, reveal that at a strain of 2.5%, composites with non-auxetic lattices exhibited a higher crack volume compared to those with auxetic lattices. This suggests that auxetic lattice structures are more effective in reducing damage and maintaining structural integrity of cementitious composites. As strain levels increased, the difference in crack volume between the two composite types narrowed slightly. However, composites reinforced with auxetic lattices consistently demonstrated lower crack volumes, highlighting their suitability for applications requiring enhanced resistance to cracking under severe strain conditions.

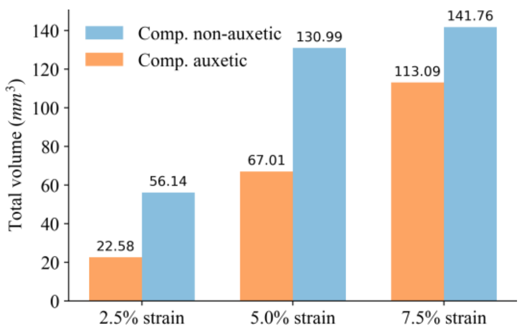

Figure 6: Crack volumes for cementitious composites with auxetic and non-auxetic lattice structures.

4.2 Interaction mechanisms

In this section, the CT results at a strain level of 2.5% was selected for further analysis of the interaction mechanisms. Figure 7 provides a detailed illustration of the microstructural damage observed in cementitious composites embedded with auxetic lattices. The dark part is the 3D printed lattice, and light part is the cementitious matrix, and the red part is the crack. On the ZY planes near the specimen's outer surfaces (left and right ZY planes), cracks appear more dispersed due to the reduced confinement from the lattice structure in these exterior regions. In contrast, the central ZY plane exhibits vertical cracks initiated at the lattice joints. These cracks were caused by the local tensile stresses when the lattice joints press against the cement matrix. This indentation force induces cracks that closely resemble tensile splitting cracks, as the matrix is being pulled apart. However, the generated cracks remain confined within the unicell, and did not penetrate the entire specimens. This is mainly because when adjacent lattice joints contact each other, a new confinement effect stabilizes the cement matrix on both sides of the crack.

The XY plane offers further insights into the role of the auxetic lattice in influencing microstructural damage. Under compression, the inward contraction of the auxetic lattice contrasts with the outward expansion of the cement matrix, driven by its natural deformation behavior (i.e., positive Poisson's ratio). This opposing deformation induces peeling of the matrix's exterior layer at the surface. In the interior regions, however, the inverse deformations of the lattice and matrix are mutually constrained, leading to fewer cracks in the core area. This interaction between the inward-contracting cellular lattice and outward-expanding cementitious matrix establishes a stabilizing effect, which limits crack propagation and lead to a uniformly distributed stress within the composites.

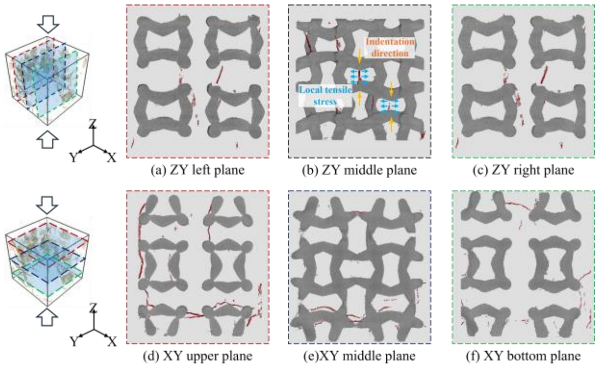

Figure 7: Microstructural damage for cementitious composites with auxetic lattice, where dark gray represents lattice and red represents cracks.

Figure 8 illustrates the microstructural damage in cementitious composites with non-auxetic lattice. It can be seen that, compared to their auxetic counterparts, these composites exhibit more vertical cracks at the ZY vertical planes. The lattice's deformation under compression, outlined by the blue dashed line indicating the unit cell's deformed shape under compression. It displaces the nodes outward and compresses the cement matrix locally. Because the reinforcement cannot provide sufficient confinement—due to its outward-expanding—this promotes vertical crack formation along the ZY planes.

In the XY planes, the damage is mainly characterized by interfacial debonding between the lattice and matrix, a cracking pattern distinct from that observed in auxetic lattice-reinforced composites. This difference arises from the higher positive Poisson's ratio of the non-auxetic lattice structure (larger than 0.3 for the maximum value), which leads to greater lateral expansion than the cement matrix. Consequently, the non-auxetic lattice's pronounced lateral deformation promotes interfacial cracking and reduces its ability to confine the matrix, ultimately increasing the likelihood of shear crack formation at the interface under uniaxial compression.

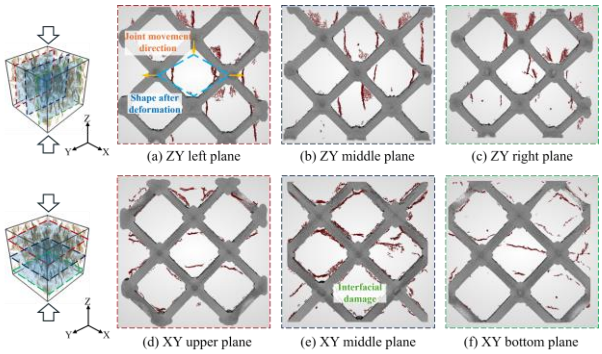

Figure 8: Microstructural damage for cementitious composites with non-auxetic lattice.

5 CONCLUSIONS

Auxetic lattice structures effectively compensate for the strength reduction associated with introducing a softer, more deformable material into the cementitious matrix. Cementitious composites reinforced with auxetic lattices demonstrated superior post-peak ductility and densification energy absorption capacity compared to both plain cement mortar and composites reinforced with non-auxetic lattice structures.

Micro-CT characterization revealed distinct microstructural damage evolution mechanisms in auxetic and non-auxetic lattice-reinforced composites. In non-auxetic lattice composites, the lack of lateral confinement on the cement matrix led to extensive crack propagation and significant interfacial damage between the lattice and the matrix, serving as the primary energy dissipation mechanism. Conversely, the inward-contracting behavior of auxetic lattices enhanced their interaction with the matrix. This resulted in better crack constraint, more uniform stress distribution within the cement matrix, and improved energy dissipation through controlled crack growth.

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REFERENCES

[1] Ren, Darui, et al., 2023. Meso-crack evolution based constitutive model for concrete material under compression. *Compos. Part B-Eng*. **265**: 110956.

[2] Asad, Mohammad, et al., 2019. Characterisation of polymer cement mortar composites containing carbon fibre or auxetic fabric overlays and inserts under flexure. *Constr. Build. Mater.* **224**: 863-879.

[3] Momoh, Emmanuel Owoichoechi, et al., 2024. A state-of-the-art review on the application of auxetic materials in cementitious composites. *Thin-Walled Struct.* **196**: 111447.

[4] Y. Prawoto, 2012. Seeing auxetic materials from the mechanics point of view: A structural review on the negative Poisson's ratio. *Comp. Mater. Sci.* **58**: 140-153.

[5] Zhao, Guoqi, et al., 2024. Preparation and compressive properties of cementitious composites reinforced by 3D printed cellular structures with a negative Poisson's ratio. *Dev. Built Environ.* **17**: 100362.

[6] Xu, Yading, et al., 2024. Spring-like behavior of cementitious composite enabled by auxetic hyperelastic frame. *Int. J. Mech. Sci.* **275**: 109364.

[7] Chen, Meng, et al., 2023. Static and dynamic compressive behaviour of 3D printed auxetic lattice reinforced ultra-high performance concrete. *Cem. Concr. Compos.* **139**: 105046.

[8] Meng, Zhaozheng, et al., 2024. Unraveling the reinforcing mechanisms for cementitious composites with 3D printed multidirectional auxetic lattices using X-ray computed tomography. *Mater. Des.* **246**: 113331.