Title
Bending and Crack Characteristics of Polymer Lattice-Reinforced Mortar

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Chapter 32
Bending and Crack Characteristics of Polymer Lattice-Reinforced Mortar

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As the construction industry moves toward precast structures, a more mechanically robust concrete is required. To provide joints with higher mechanical toughness, we propose reinforcing the mortar with a polymeric lattice. This study considers the mechanical effects of reinforcing concrete with a polymeric lattice and compares this new technique against the standard fiber-reinforced method. We investigate the octet lattice, which is notable for its high specific strength. Lattices with 23.4 mm unit cells were prototyped out of polylactic acid using a thermoplastic extrusion-based 3D printer. These lattices were placed in a rectangular mold, infiltrated with concrete, and vibrated. The resulting specimens were tested for flexural strength in four-point bending on a hydraulic testing machine. Bending test results show that the lattice-reinforced beams achieve a net deflection at peak load that is 2.5 times greater than that of the fiber-reinforced beams. Further, the lattice-reinforced beams obtain toughness and peak load values comparable to the fiber-reinforced beams while allowing for easier processing. Fabrication of these lattice structures for use in construction can readily be scaled, as the polymeric lattices can be manufactured through injection molding.

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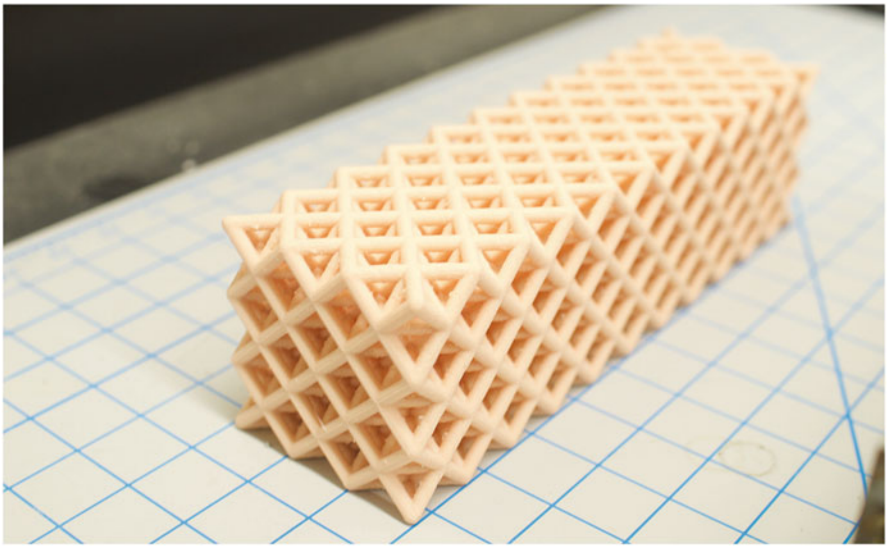

Fig. 32.1 A polymeric octet lattice beam for use as concrete reinforcement

1 Introduction

In 1961, Buckminster Fuller patented his vision for building walls, roofs, and floors constructed out of struts in an octahedron-tetrahedron arrangement [1]. Since then, the octet lattice (shown in Fig. 32.1) has been experimentally shown to have a high specific strength [2]. Other research has focused on the optimizing the octet shape for bending performance [3], and Chiras has found that members in metallic octet lattices fail due to material yielding (in tension) or buckling (in compression) [4]. O'Masta's experiments with metallic lattices show that, after a critical member thickness, the octet's fracture toughness increases as the member diameter increases [5].

Polymer fibers are usually added to concrete beams for improved crack resistance. However, the amount of polymeric fibers that can be incorporated into a mortar is limited to about 5% by volume due to practical reasons. We demonstrate the ability to use lattice reinforcement with a polymeric volume fraction up to 30.5% and compare the lattice reinforcement with randomly dispersed polymer-fiber reinforcement and unreinforced beams.

2 Materials and Methods

We 3D-printed polymeric lattices out of polylactic acid (PLA) on a Type A Pro fused-deposition modeling machine using a 0.4 mm nozzle and 0.2 mm layer height. Though the octet lattice is very complex, its optimal angles and size allowed it to be

Table 32.1 Mortar mix weight proportions for the two mortars

Reinforcement type	Cement	Fly ash	Water	Fine aggregates	Superplasticizer	Fibers
Plain and lattices	1.00	0.18	0.60	2.05	0.0024	0
8 mm PVA fibers	1.00	0.10	0.55	1.01	0.0018	0.05

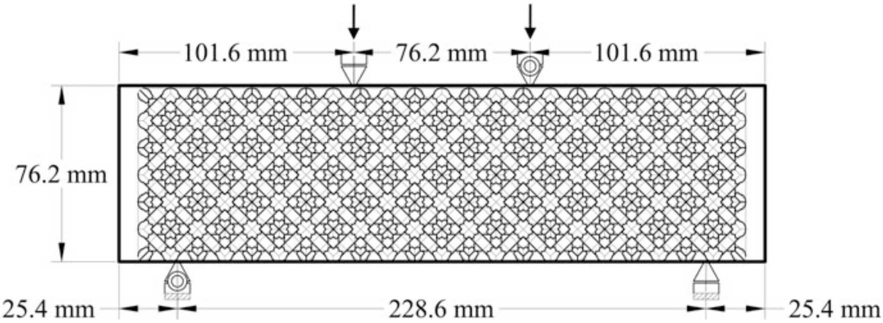

Fig. 32.2 Four-point beam bending testing setup, with the internal lattice visible

printed without support material. We printed two lattices with a 3.175 mm member diameter and three lattices with a 4.62 mm member diameter. Variation in the 3D printing process resulted in up to a 2.5% weight variation in lattices of a given member diameter.

High flowability is required for the concrete to infiltrate the dense polymer lattices. This is achieved by using a high water-to-cementitious materials ratio of 50% and a high-range, water-reducing admixture (ADVA Flex superplasticizer). The mortar mix (shown in Table 32.1) replaces 15% of the portland cement with ASTM C618 Class F fly ash [6] and contains fine aggregates (P.W. Gillibrand #90 Silver Sand, SG = 2.6). Once mixed, the mortar reached a flow diameter of 25 mm, based on the ASTM C1437-07 flow test [7]. A second mortar, shown in Table 32.1, was made and included 8 mm polyvinyl alcohol (PVA) fibers at a 2.88% fiber volume fraction. This mix was so viscous that it was not possible to perform the ASTM C1437-07 flow test [7].

The lattice reinforcement was placed into 76.2 mm × 76.2 mm × 279.4 mm rectangular beam molds. The mortar mixture was then poured into the molds and vibrated until it completely infiltrated the lattices. To make the unreinforced beams, the mortar was simply poured into the mold and vibrated; the fiber-reinforced beams were made in a similar fashion, accompanied by rodding. The beams were stored in a fog room for 7 days.

We tested the beams in four-point bending, as shown in Fig. 32.2, on a Universal Testing Machine (Baldwin Southwark Tate-Emery Testing Machine) in accordance with ASTM C78M [8]. We used LabVIEW for data capture from the force sensor and two linear variable differential transformers (LVDTs). One LVDT was placed on the beam's front side (shown in Fig. 32.2), and the other LVDT was placed on the back; the displacement was taken as the average of the LVDT readouts.

3 Results and Discussion

Whereas the unreinforced beams revealed a flat fracture surface, the lattice-reinforced beams developed the textured fracture surfaces shown in Fig. 32.3. Mortar beams with polymeric lattices formed multiple cracks. The crack propagation was restricted, as shown in Fig. 32.4, by the polymeric lattice.

We analyzed the test data in accordance with ASTM 1609 [9]; toughness is defined as the area under the load-displacement curve up until a displacement of $L/150$, where L is the beam span. We used MATLAB's "trapz" function to calculate the toughness for our experiments, where $L = 228.6$ mm. The lattice-reinforced beams exhibit multiple peaks (shown in Fig. 32.5), where each peak corresponds to a

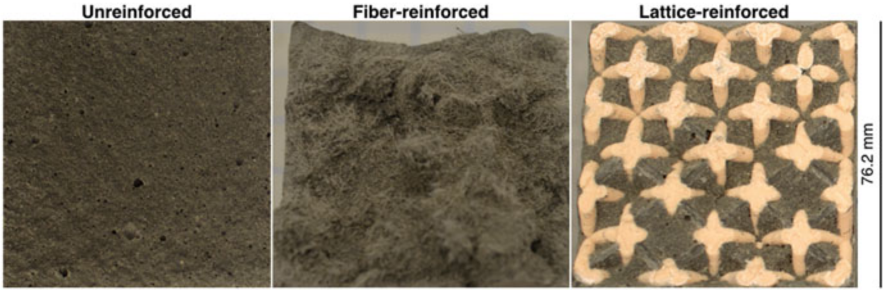

Fig. 32.3 Fracture surfaces of plain mortar, fiber, and lattice-reinforced beams

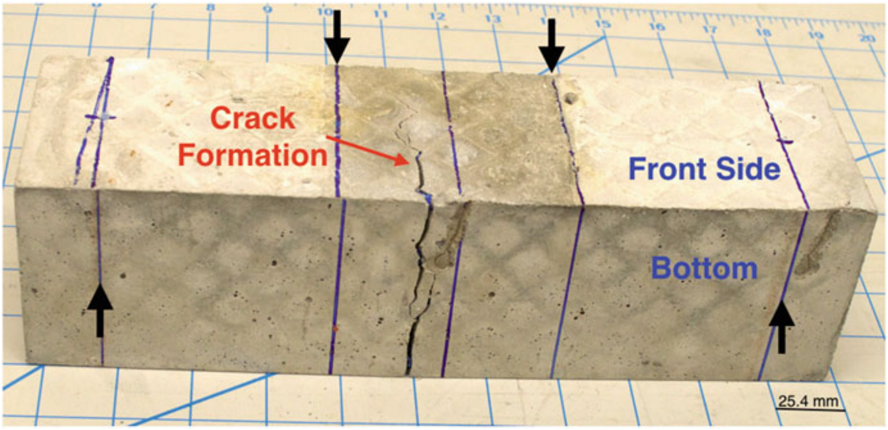

Fig. 32.4 Crack propagating through a PLA-reinforced mortar beam

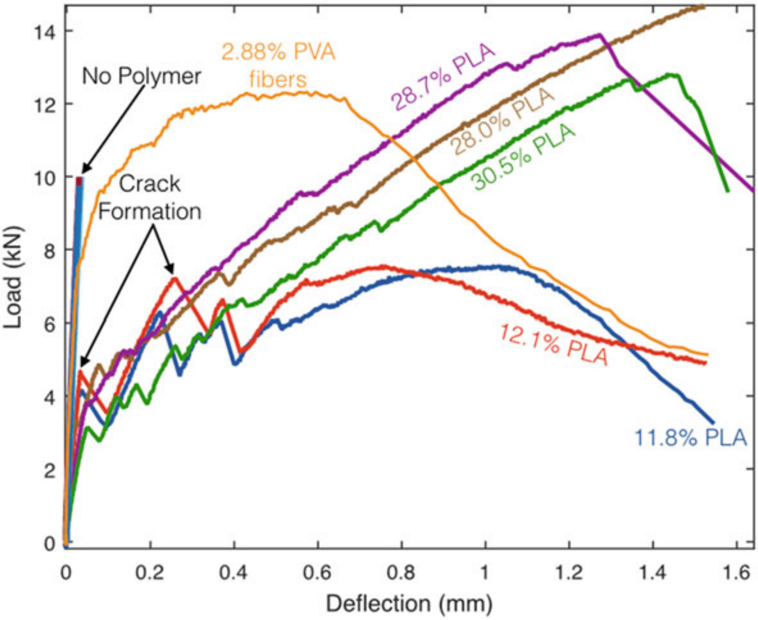

Fig. 32.5 Force vs deflection profiles for plain, fiber, and lattice beams

Table 32.2 Material characteristics of tested beams

Beam description	Toughness	First peak load	Peak load	Deflection at peak load
No polymer	0.185 J	10.0 kN	10.0 kN	0.0345 mm
No polymer	0.166 J	10.0 kN	10.0 kN	0.0293 mm
No polymer	0.158 J	9.74 kN	9.74 kN	0.0298 mm
2.88% PVA fibers	14.3 J	6.33 kN	12.3 kN	0.557 mm
11.8% PLA lattice	9.07 J	4.17 kN	7.56 kN	0.985 mm
12.1% PLA lattice	9.29 J	4.67 kN	7.56 kN	0.750 mm
28.0% PLA lattice	14.9 J	3.31 kN	14.6 kN	1.52 mm
28.7% PLA lattice	16.4 J	5.25 kN	13.9 kN	1.27 mm
30.5% PLA lattice	13.6 J	3.15 kN	12.8 kN	1.43 mm

new crack forming. As such, we report the first peak load and the overall (max) peak load in Table 32.2. For plain beams, the first peak load and peak load are equal, since they did not experience multiple crack formations.

4 Conclusion

While the polymeric lattice provides initiation sites for cracks through the mortar, it also serves to deflect the cracks and prevents them from quickly propagating through the beam. The three lattice-reinforced beams with the highest amount of PLA attain toughness values 88 times higher than the toughness of plain beams; they also reach a peak load that is 1.4 times greater than the peak load reached by the plain mortar beams. The reduced stiffness displayed by lattice-reinforced beams is to be expected, based the rule of mixtures, due to the higher polymeric ratio and may not be relevant in some applications. While the lattice-reinforced beams obtain toughness and peak load values comparable to the fiber-reinforced beams, the lattice-reinforced beams achieve a net deflection at peak load that is 2.5 times greater than that of the fiber-reinforced beams. Furthermore, the fiber-reinforced mortar presents workability issues, due to its low flowability, while the lattice reinforcement can be quickly injection molded from polymers and then easily infiltrated with non-fiber-containing mortar or concrete. Manufacturing from a recycled polymer would make this method inexpensive and would provide a new usage stream for used polymers.

We can adjust the polymeric lattice to concrete weight ratio to achieve desired mechanical properties and are exploring other lattice materials and geometries. These mechanical properties indicate that lattice-reinforced concrete composite beams are promising for construction applications. We envisage lattice reinforcement for use in nonbearing members, such as in building façade systems, where the polymeric structure can be designed to support bending loads.

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