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FLEXURAL RESPONSE OF CEMENTITIOUS MORTAR BARS REINFORCED BY 3D PRINTED POLYMERIC MESH

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Abstract

In order to improve the behaviour of cementitious material under in bending, 3D printed polymeric lattice meshes were used as an alternative to fibre reinforcement. Lattice meshes with different cell sizes and different surface roughness were designed and printed. Plain mortar samples and reinforced samples were casted. After curing, 4-point bending tests were performed. The tests results show that, with the right designs, strain-hardening behaviour is achieved. Simultaneously, the flexural strength and flexural deflection capacity of mortar bars are increased. Crucial to this effect, a small mesh size (especially in the region of highest moment). Creating ridges on the reinforcement to increase the surface roughness of the reinforcement also showed promise in improving the deflection capacity and flexural strength.

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, been studied and used in many fields such as aerospace [1], bio-medicine[2, 3] and energy [4] for its highly customizability, automatized manufacturing process and resource saving since it was developed in 1980s [5]. In construction industry, the application of 3D printing technology on cementitious materials has also attracted intensive attention recently. Some studies [6-8] have shown its potential of changing this conventionally laborious and energy consuming industry to be more automatized and digitalized. For concrete, which is one of the most commonly used building materials, a big challenge that may be tackled with 3D printing is the brittleness of its cementitious matrix. Several studied attempted to tackle this problem such as combining reinforced concrete with 3D printed plain concrete [9] and using fibre reinforced concrete as printing ink [10]. Another possibility is the printing of reinforcement. Comparing to traditional reinforcement, 3D printed reinforcement has more freedom of design to improve the performance of reinforcement such as increasing bond strength by printing rough surface[11, 12].

In the present study, lattice structure mesh [13] was adopted and printed as reinforcement for mortar bars. Flexural response of these reinforced mortar bars was tested using 4-point bending test. The influence of different reinforcement designs on flexural strength and deflection capacity of mortar bars are analysed.

2. MATERIALS AND METHODS

2.1 Fabrication of the reinforcement

Triangular lattice was adopted and printed as reinforcement and two cell sizes were used respectively forming fine mesh, coarse mesh and mixed mesh. In the mixed mesh design, small cells were only used in regions with the highest bending moment in a 4-point bending test (Figure 1). For better bonding between matrix and reinforcement, ridges were designed on surface of mixed lattice mesh and the total volume of the ridged design is kept the same with plane surface lattice mesh. Figure 2 shows four final designs. Parameters of the four meshes are shown in Table 1. In order to place the reinforcement in the middle of the mortar bar, support feet were designed at the four corners of all lattice mesh.

Table 1 Design parameters of lattice meshes

No.	Mesh type	Diameter of cell inscribed circle (mm)	Width (mm)	Length (mm)	Surface
T4	Triangular	4	24	140.87	Plane surface
T8	Triangular	8			
TM	Triangular	4 and 8			
TMr	Triangular	4 and 8			Ridged

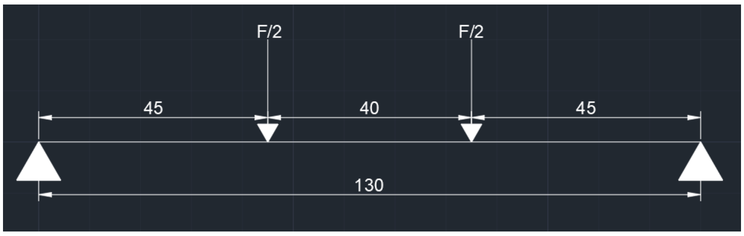
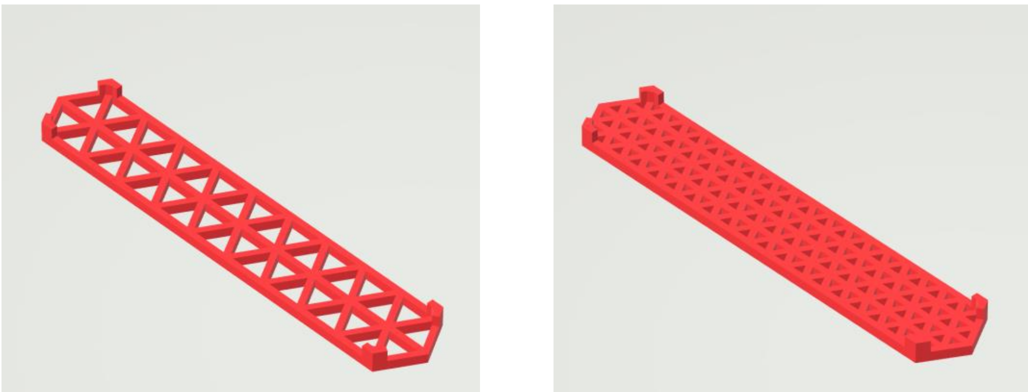
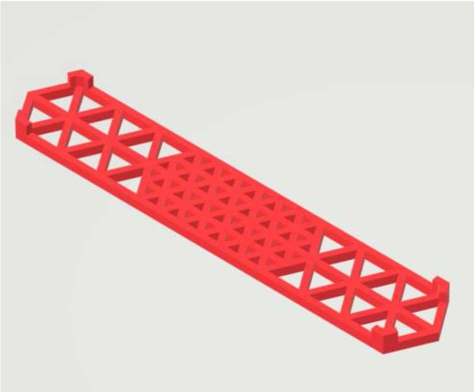


Figure 1 Scheme of 4-point bending test



(a) (b)



(c)

(d)

Figure 2: Reinforcement designs of (a)T8, (b)T4, (c)TM and (d)TMr

Acrylonitrile Butadiene Styrene (ABS) material was used to print the reinforcement for its relatively high properties and high alkaline resistance among most commonly used 3D printing materials.

The designed lattice meshes were printed by a commercial fused deposition modelling (FDM) printer Ultimaker 2+. Printing parameters such as printing temperature, printing speed and layer height were kept constant in every print and they are shown in Table 2. The printing direction was chosen to make sure the layers were parallel to normal stress as it was the easiest, and also yielded higher tensile strength [14]. In order to get better printing quality, the lattice meshes were printed with the feet towards the upper side making sure no large overhangs occur during printing.

Table 2 Printing parameters

Printing parameters	Configurations
Temperature (°C)	260
Layer height(mm)	0.2
Printing speed(mm/s)	40
Nozzle diameter(mm)	80
Filament diameter(mm)	2.85

2.2 Casting and curing

The printed meshes were sanded for 30 seconds with 125 μm sand paper before casting to increase the bond between reinforcement and cementitious matrix. The positions of reinforcement were marked on Styrofoam moulds. Then they were placed in Styrofoam moulds with their feet pressed into the moulds for 1mm and glued with silicon rubber to make sure the reinforcement stays in the middle and does not move during vibration.

Then materials were weighted according to the mix proportion in Table 3 . After four minutes of materials dry mixing, water and superplasticizer were added and four minutes of mixing was performed. Subsequently, the materials were casted in the prepared moulds and vibrated for 30 seconds. Samples were numbered and demoulded after two days. Then they were cured until 7d and 14d (only TM samples) in a curing chamber (20 ±2°C°C, 96 ±2%RH). Samples were cut according to the marks on the testing day before test. The sample size is 180mm × 30mm × 8mm.

Table 3 Mix proportion, g/l

CEM I 42.5	Fly ash	Sand (0.125~0.250 mm)	Superplasticizer (Glenium 51)	Water
550	650	550	2	395

2.3 Four-point bending test

4-point bending tests were performed on cured samples using a servo hydraulic press (INSTRON 8872) under displacement control with a constant rate of 0.01mm/s. The load was measured by load cell and the deflection was measured by two linear variable differential transducers (LVDTs) placed at the mid-span. For each sample, the cross section was measured and calculated before test.

3. RESULTS

For proper comparison between the samples, the following parameters were chosen to be calculated:

- **Flexural strength (MPa)**: The maximum flexural stress.
- **Flexural deflection capacity (mm)**: The vertical displacement under the loads corresponding to the maximum flexural stress.

3.1 Flexural strength and deflection capacity

Representative curves of plain mortar samples and reinforced samples of the 4-point bending tests are shown in Figure 3. As can be seen from the 7 days flexural stress-deflection curves, plain mortar sample (Ref) fails immediately after matrix flexural strength is reached which is typical behaviour for plain mortar bar. Comparatively, reinforcement significantly changes behaviour of mortar bars. For T8 samples, reinforcement took over the load after the first macro crack and the load increased but lower than matrix flexural strength until second crack appeared. Afterwards, typical large strain behaviour of polymers after yielding can be observed. For T4 and TM samples, so called "strain hardening" behaviours can be observed which is similar to fibre reinforced and textile reinforced concrete [15, 16]. After the matrix flexural strength is reached, first macro crack formed and load suddenly dropped and subsequently the reinforcement started to bear loads. Afterwards, loads started to increase higher than the first peak and multiple cracks formed before the peak load is reached. Multiple cracks can be seen during and after the tests on the reinforced samples (Figure 4).

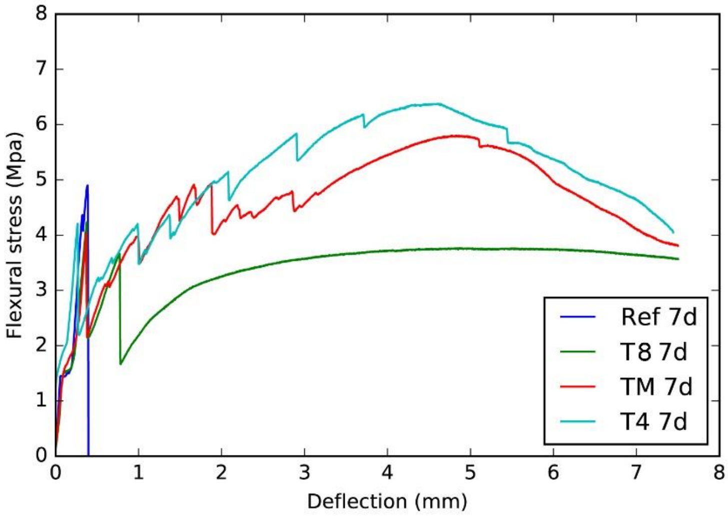


Figure 3: Flexural-deflection curves of 7d samples

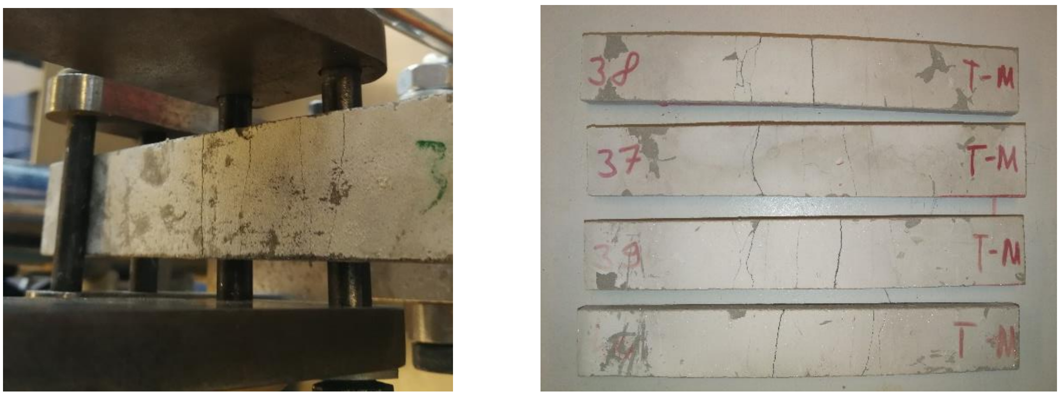


Figure 4 Samples of (a)during test and (b)after test

The influence of reinforcement on performance of mortar bars is more obvious in the flexural deflection capacity diagram (Figure 5). Mortar bars reinforced with coarse mesh(T6) don't show obvious strain hardening behaviours while mortar bars reinforced by fine mesh (T4) and mixed mesh (TM) exhibit obvious strain hardening behaviour. For T4 and TM, both of them have fine mesh in the regions with highest bending moment, the deflection capacity and flexural strength are identical which indicates that mixed mesh is an optimal design as reinforcement for the mortar bars in this study because it uses less materials and provide enough reinforcing effect.

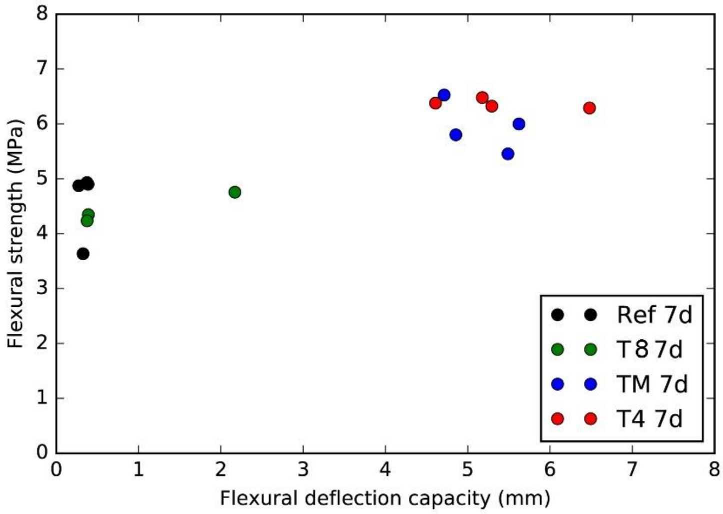


Figure 5 Flexural deflection capacity

For samples with longer curing time, it can be found in Figure 6 that the stress of the first crack in 14d TM mortar bars is higher because the matrix became stronger after longer curing. After the first crack, 14d TM samples also exhibit similar strain hardening behaviour as 7d samples during the 4-point bending test.

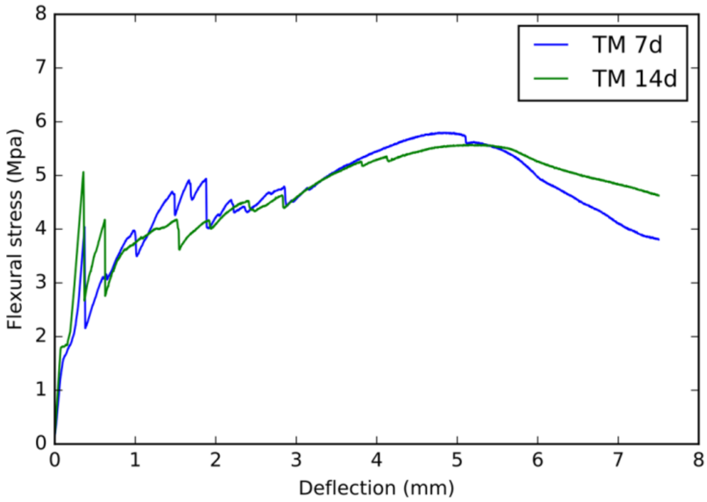


Figure 6 Flexural-deflection curves of 14d and 7d TM samples

3.4 Influence of surface roughness

As can be seen in Figure 7, the samples with a ridged surface showed a higher flexural strength and a higher flexural deflection capacity than the plane surface samples. Because of the limitations of the measuring range LVDT, the curves could only be reliably measured until a deflection of 7.5 mm. However, the ridged samples showed a tendency to keep strength for longer after the 7.5 mm boundary. The difference shows that surface roughness is an important factor that influence the performance of reinforced mortar bars. A possible reason of the difference is that during the tests, as the matrix and reinforcement are strong enough, cracks mainly propagated along the weakest part i.e. the interface between matrix and reinforcement. In mortar bars with ridged reinforcement, it needs much higher energy to propagate through the fluctuating surface so that the ridged reinforcement can provide more ductility for mortar bars.

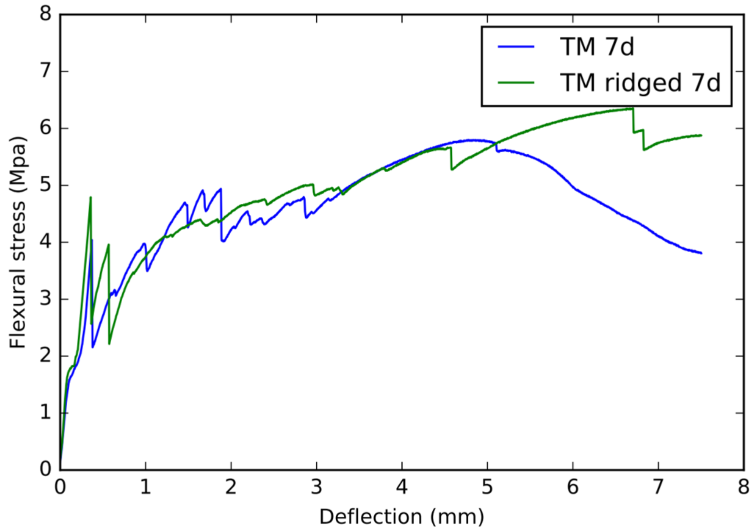


Figure 7 Flexural-deflection curves of surface ridged and plane surface 7d TM samples

4. CONCLUSIONS

According to the 4-point bending test results on mortar bars. Several conclusion can be drawn as below:

- By using proper reinforcement designs, flexural strength and ductility of mortar bars are increased by 3D printed ABS lattice reinforcement. For fine mesh reinforced and mixed mesh reinforced mortar bars, strain-hardening behaviour can be achieved which indicates that cell size is a crucial factor of the reinforcing effect.
- TM with mixed reinforcement is an optimal design because it exhibits similar strain-hardening behaviour and costs less material as it only has fine mesh in the region with highest bending moment.
- Increasing surface roughness can improve the performance of reinforced mortar bars. Possible reason is the ridged surface arrested crack propagation along the interface between matrix and reinforcement.

Comparing to traditional reinforcement, 3D printed reinforcement can be customized according to different loading condition. An optimal design of reinforcement can be obtained with less material cost and the same reinforcing effect. During limited time, flexural response of mortar bars with longer curing time were not tested, further research will focus on these tests.

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