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**Mechanical properties**

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# 1 Development of Strain Hardening Cementitious Composite 2 (SHCC) reinforced with 3D printed polymeric reinforcement: 3 mechanical properties

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5  
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## 7 8 **Abstract**

9 Cracking in concrete needs to be limited for esthetical and durability reasons. Currently, this  
10 is commonly done by using steel rebars in the structure or fiber reinforcement in the  
11 material. With certain fiber types and micromechanical design, it is even possible to create  
12 cement-based materials with steel like (i.e. quasi-plastic) properties – so called strain  
13 hardening cementitious composites (SHCCs). In this paper, an alternative approach for  
14 creating SHCC – through use of additive manufacturing to create polymeric reinforcement  
15 meshes – is proposed. Different designs are manufactured, casted in the cementitious  
16 matrix, and tested in four-point bending and uniaxial tension. It was found that, with proper  
17 designs, it is possible to create cementitious composites with deflection hardening or strain  
18 hardening properties. Furthermore, with proper design, multiple cracking behavior of  
19 conventional SHCC can be replicated. In addition, numerical simulations were performed  
20 using the Delft lattice model. Four point bending tests on mortar bars reinforced by two  
21 different mesh designs were simulated and the results show good agreement with the  
22 experiments. This research shows great potential of using additive manufacturing for  
23 creating SHCCs with customizable properties.

24 **Key words:** *Strain hardening cementitious composite; 3D printing; Polymeric reinforcement,*  
25 *Delft lattice model.*

## 26 27 1. Introduction

28 Concrete is the most widely used construction material in the world. Compared to other  
29 construction materials, such as e.g. steel and timber, concrete structures are more resistant to  
30 aggressive environmental conditions. However, while concrete shows excellent resistance to  
31 compressive loads, it is relatively weak in tension. Therefore, steel reinforcement is added to  
32 take over the tensile loads. Reinforcing steel is, in general, protected from corrosion by a  
33 passive film that forms around it in an alkaline environment of the concrete pore solution

34 [1]. Over the lifetime of a structure, this protective film might break down due to  
35 carbonation [2, 3] or chloride ingress [1, 4]. Once this happens, active corrosion of the  
36 reinforcement will start, causing loss of steel cross section [5] and, eventually, cracking [6],  
37 and spalling of the concrete cover [7]. Therefore, it is important that the quality of the  
38 concrete cover is ensured to protect the reinforcement. However, reinforced concrete  
39 structures are commonly cracked. Wide cracks present fast pathways for moisture [8],  
40 carbon dioxide [9] and chloride ingress [10, 11], resulting in fast corrosion initiation and end  
41 of service life [12]. Therefore, limiting crack width is crucial to ensuring the durability of  
42 reinforced concrete structures.

43 The weak tensile response of concrete can be overcome by the addition of fibers to the  
44 material [13]. Commonly used fiber types include steel [14], glass [15] and natural fibers [16].  
45 The role of fiber reinforcement is mainly to increase the fracture toughness, prevent crack  
46 localization, and reduce the crack width in concrete. Furthermore, in recent decades, a new  
47 class of fiber reinforced concrete – strain hardening cementitious composite (SHCC) – has  
48 been developed. SHCC is a class of ultra-ductile fiber reinforced composites developed in  
49 the early 1990s [17]. It is characterized by a large strain capacity (sometimes more than 5%)  
50 and a strain hardening behavior in tension achieved through tightly spaced distributed  
51 microcracking [18]. Typically, SHCCs are reinforced with a relatively small amount (around  
52 2% by volume) of polyvinyl alcohol (PVA) fibers [19, 20], although other fiber types such as  
53 polyethylene have also been used [21]. Practical application of fiber reinforcement in  
54 concrete is not without problems – fiber orientation is influenced by execution parameters,  
55 such as the size of the structural member and the direction of the concrete flow during  
56 casting [22, 23]. Furthermore, agglomeration of fibers and weak spots in the material may  
57 occur. This can be overcome to a certain extent by using a pre-fabricated reinforcement, as is  
58 the case in textile reinforced concrete (TRC). TRC elements typically consist of several layers  
59 of textile fabrics of multi-filament yarns made of alkali-resistant glass or carbon, which are  
60 embedded in a fine-grained concrete or mortar [24]. Similar to SHCC, TRC shows strain  
61 hardening and multiple cracking in tension [25]. It is therefore a viable alternative to SHCC.  
62 In recent years, an alternative approach for creating complex geometries that may be used as  
63 micro-scale reinforcement in concrete has emerged. Recent developments in additive  
64 manufacturing (3D printing) [26] techniques for polymers (e.g. fused deposition modelling

65 [27, 28]) enable creating complex geometries. Reinforcement meshes created using additive  
66 manufacturing techniques could be used to replace fiber reinforcement. Although in the  
67 field of civil engineering most attention has been given to 3D printing of complete concrete  
68 structures [29] and structural reinforcement cages [30], recently attention has been given to  
69 printing reinforcement. Farina et al. [31] used additive manufacturing to create polymeric  
70 and metallic reinforcement for mortar elements subjected to bending. In their study,  
71 additive manufacturing was used to control the surface roughness of the reinforcement.  
72 Nam et al.[32] used fused deposition modelling to create structures to replace conventional  
73 fiber reinforcement in mortar in order to avoid problems associated with conventional fiber  
74 reinforcement such as e.g. fiber clustering. Rosewitz et al.[33] used 3D printed bio-inspired  
75 polymeric structures as reinforcement for cement mortar to enhance the performance of  
76 cementitious material. These publications show that there is great potential in using additive  
77 manufacturing techniques for creating reinforcements which have potential to replace  
78 conventional fiber reinforcement.

79 Numerical simulations can be of great help in analyzing experimental trends. In previous  
80 studies [34, 35], lattice models were successfully used to simulate fracture processes of steel  
81 reinforced and fiber reinforced cementitious materials. The basic principle of the lattice  
82 model is to discretize a continuum to a lattice network that consists of truss or beam  
83 elements. In general, linear elastic properties are assigned to the lattice elements. As soon as  
84 a prescribed displacement or load is imposed on the lattice network, a set of linear elastic  
85 analyses is carried out. In each loading step, one critical element is removed when element  
86 stress exceeds its strength. Reaction load and displacement are recorded in each step and the  
87 analysis is repeated until the entire lattice system fails. Failed element represents micro  
88 cracks in the material, in this sense the load-displacement response and material cracking  
89 behavior can be simulated.

90 In this work, development of strain hardening cementitious composites (SHCCs) that use 3D  
91 printed polymeric meshes with two dimensional triangular patterns, instead of discrete fiber  
92 reinforcement is presented. Different reinforcement geometries are manufactured and tested  
93 in four-point bending and uniaxial tension. Furthermore, numerical simulations of the  
94 experiments are performed using the lattice model. The experiments and simulation results  
95 are then critically discussed and suggestions for future work are given.

## 96 2. Materials and method

### 97 2.1. Materials

98 Cementitious materials reinforced with 3D printed polymeric meshes have been fabricated.  
 99 The matrix material was a fine-grained cementitious mortar containing CEM I 42.5 N and fly  
 100 ash as binder materials, with a water-to-binder ratio of 0.33. The assumed mixture was used  
 101 to develop SHCC in [36], meanwhile relatively high fluidity was achieved making it easier  
 102 to fill the hollow cells of the printed reinforcement in this study. The mixture is listed in  
 103 Table 1.

104 *Table 1. Mixture design of the matrix material (g/l), adapted from [36]*

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

105  
 106 Polymeric reinforcement meshes were manufactured using a commercially available FDM  
 107 3D printer Ultimaker 2+ (Figure 1). In FDM, the model is printed layer by layer, from the  
 108 bottom up. As a result, overhangs may be difficult to print and result in poorer quality.  
 109 Therefore, relatively simple mesh patterns were selected in this study, as described below.  
 110 Acrylonitrile Butadiene Styrene (ABS) was used as the printing material (i.e. filament). ABS  
 111 has excellent mechanical properties, interlayer adhesion, minimal warping, reliable bed  
 112 adhesion and high alkaline resistance [37], which is important for use in cement-based  
 113 materials.  
 114 Printing parameters may affect the mechanical properties of the resulting structure.  
 115 Therefore, they are kept constant throughout this research. Printing parameters used are  
 116 given in Table 2. Printing direction has a significant effect on the mechanical properties [37,  
 117 38]. Therefore, printing was performed in the direction parallel to the normal stress,  
 118 resulting in maximum strength.

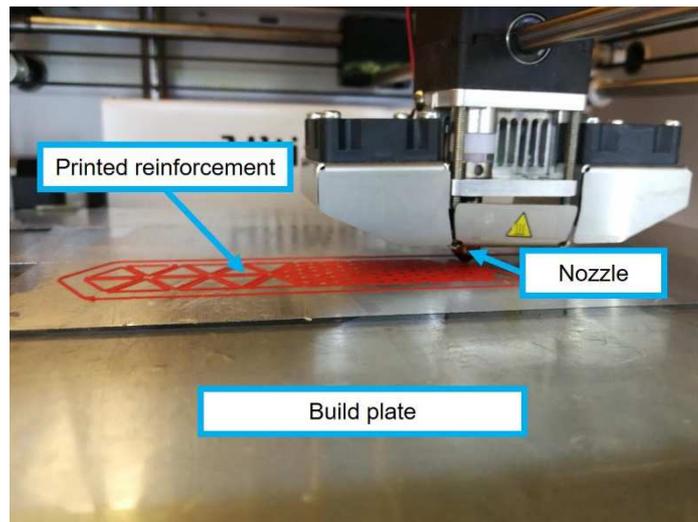


Figure 1 Schematics of reinforcement printing setup in the Ultimaker 2+.

119

120

121 Table 2. Printing parameters for reinforcement meshes used

<i>Printing parameter</i>	<i>Configuration</i>
Nozzle diameter (mm)	0.8
Temperature (°C)	260
Layer height (mm)	0.2
Line width (mm)	0.7
Infill density (%)	100
Infill pattern	Lines
Printing speed (mm/s)	40

122

## 123 2.2. Reinforcement designs

124 In this study, reinforcements with three different patterns were manufactured and tested.

125 All patterns are based on triangular lattices, as shown in Figure 2 and Figure 3. As can be

126 seen, different sizes of triangles are used, and the cross section of the reinforcement along

127 the printed mesh is not constant. For small triangles, large triangles and mixed triangles the

128 cross-sectional reinforcing ratio of different patterns is listed in Table 3 and the triangle

129 pattern size parameters are shown in Figure 2d and Figure 2e. The small triangle pattern has

130 an overall higher cross-sectional reinforcing ratio, therefore, it was expected that smaller

131 triangle size (Figure 2b) will provide a better reinforcement effect compared to larger

132 triangles (Figure 2a) and, as a result, better global behavior. The pattern in Figure 2c is a mix

133 of the two previous patterns: large triangles are used in the outer parts of the mesh, while a

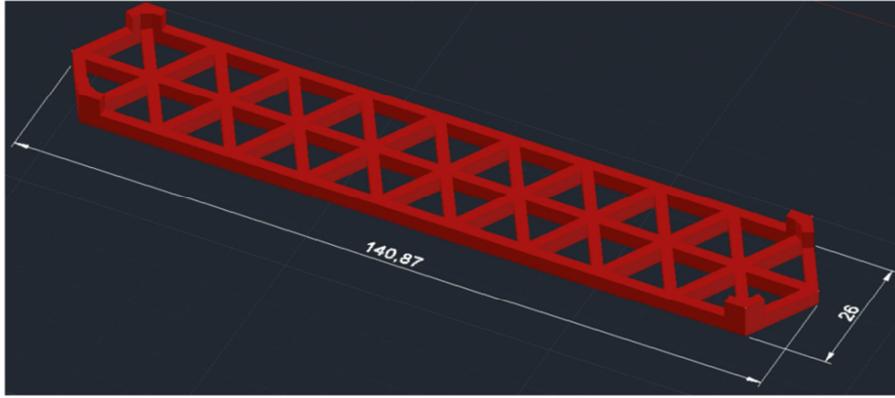
134 denser mesh is created in the middle. This pattern was used only in four-point bending tests.  
 135 In four-point bending, the middle portion of the specimen is subjected to a constant bending  
 136 moment, which is higher than the outer regions, and thus requires more reinforcement. In  
 137 that case, additive manufacturing may be able to more optimally utilize the reinforcement  
 138 compared to traditional textile or fiber reinforcement. Therefore, the pattern shown in  
 139 Figure 2c was developed to test that it is possible to create a simple functionally graded  
 140 material, in which the material structure (in this case, printed “fiber” reinforcement) is  
 141 adjusted to the actual stress state, through use of additive manufacturing.

142 *Table 3 Cross sectional reinforcing ratio of different reinforcement patterns*

Reinforcement pattern	Cross sectional reinforcing ratio (%)
Large triangles	12.5 ~ 17.5
Small triangles	17.5 ~ 32.5
Mixed triangles	12.5 ~ 32.5

143  
 144 In addition to different patterns, roughness of the printed reinforcement mesh may have an  
 145 effect on the bond and, consequently, the mechanical properties of the composite material.  
 146 Therefore, for each of the loading conditions tested (i.e. four-point bending and uniaxial  
 147 tension, respectively), one of the patterns was additionally roughened by introducing a  
 148 rough profile on one side of the printed mesh as shown in Figure 3d (in order to avoid big  
 149 overhangs during 3D printing which may result in poor printing quality, only the upper  
 150 side of the mesh was printed with rough profile). These were mixed triangles pattern and  
 151 the large triangles pattern for four-point bending and uniaxial tension experiments,  
 152 respectively. A summary of all patterns and tests is given in Table 4. Note also that all  
 153 reinforcement meshes were produced with “studs” that enabled the meshes to be easily  
 154 positioned in the middle of the specimen during casting.

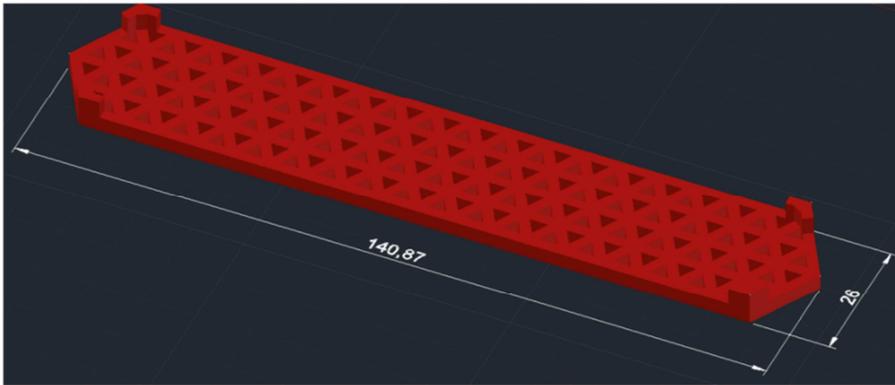
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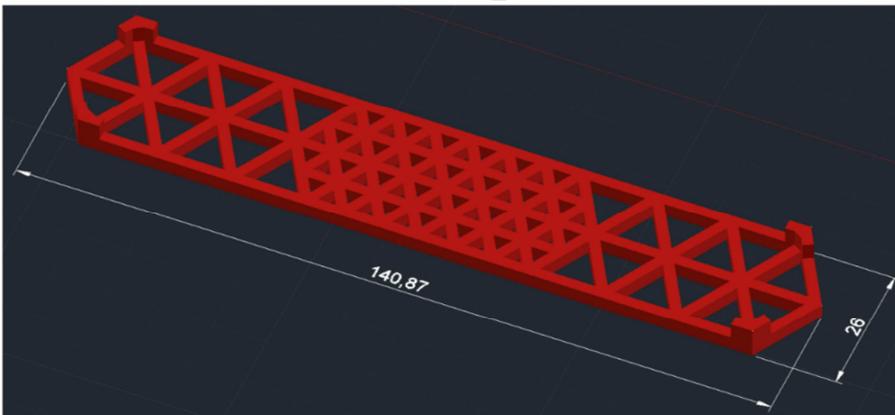
(a)



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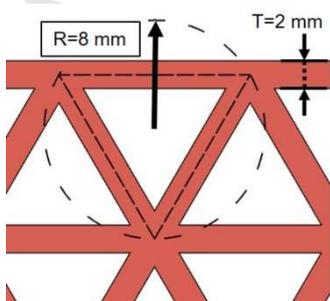
(b)



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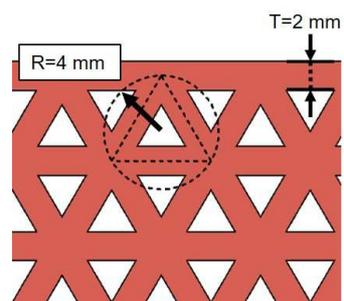
(c)



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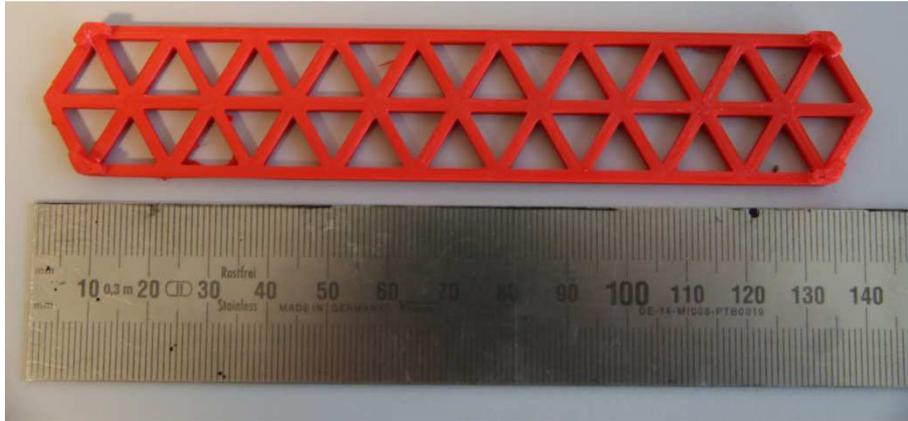
163

(d)



(e)

164 Figure 2. Design of polymeric reinforcement meshes and printed reinforcement. (a) large triangles;(b) small triangles; (c)  
165 mixed triangles (dimensions are in mm); (d) design parameters of large triangles; (e) design parameters of small triangles.



166

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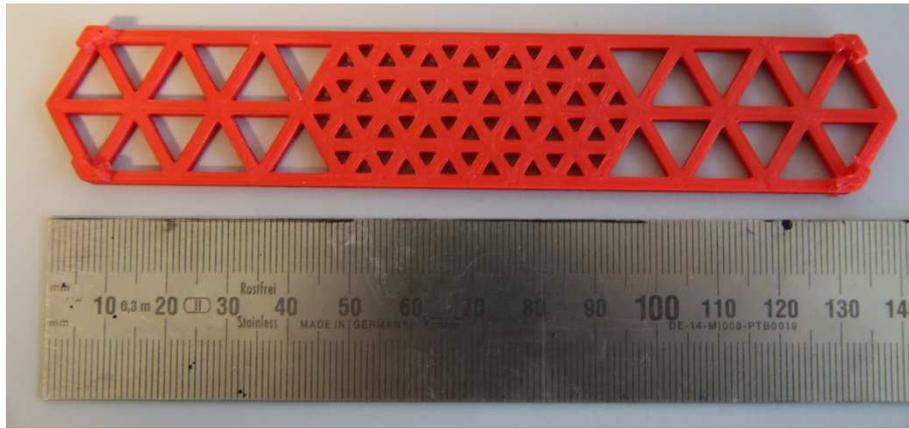
(a)



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169

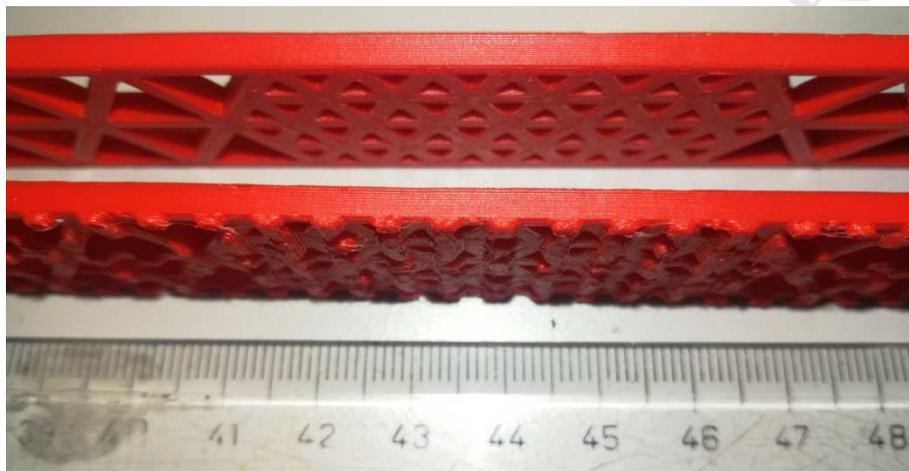
(b)



170

171

(c)



172

173

(d)

174

Figure 3. Printed reinforcement with (a) large triangle pattern; (b) small triangle pattern; (c) mixed triangle pattern;

175

(d) smooth surface and rough surface

176

177

Table 4. A summary of all designs and tests

Triangle mesh type	Surface profile	Series ID	Diameter of cell circumscribed circle (mm)	Four-point bending	Uniaxial tension	Age
None	/	Ref, Ref <sub>28</sub>	/	Yes	Yes	7d, 28d
Large	Smooth	LT	8	Yes	Yes	7d
Large	Rough	LT <sub>R</sub>	8	No	Yes	7d
Small	Smooth	ST, ST <sub>28</sub>	4	Yes	Yes	7d, 28d

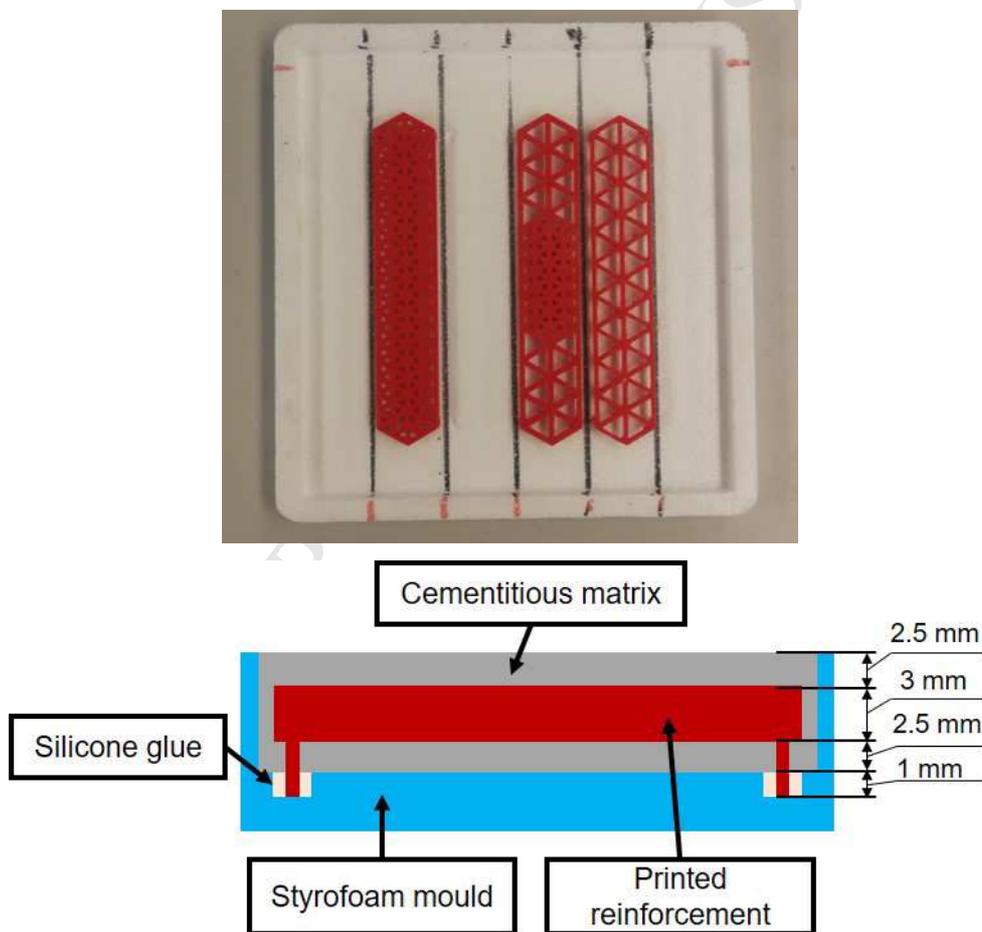
Mixed	Smooth	MT, MT <sub>28</sub>	4,8	Yes	No	7d, 28d
Mixed	Rough	MT <sub>R</sub>	4,8	Yes	No	7d

178

## 179 2.3. Casting and curing

180 The bottom surfaces of printed meshes were sanded for 30 seconds with 125 $\mu$ m sand paper  
 181 before casting to remove the glue layer in contact with 3D printer build plate. The positions  
 182 of reinforcement were marked on Styrofoam moulds. Then they were placed in Styrofoam  
 183 moulds (190 x 180 x 8 mm) with their studs pressed into the moulds for 1mm (shown in  
 184 Figure 4) and glued with silicone rubber to make sure the reinforcement stays in the middle  
 185 and does not move during vibration.

186



187

188

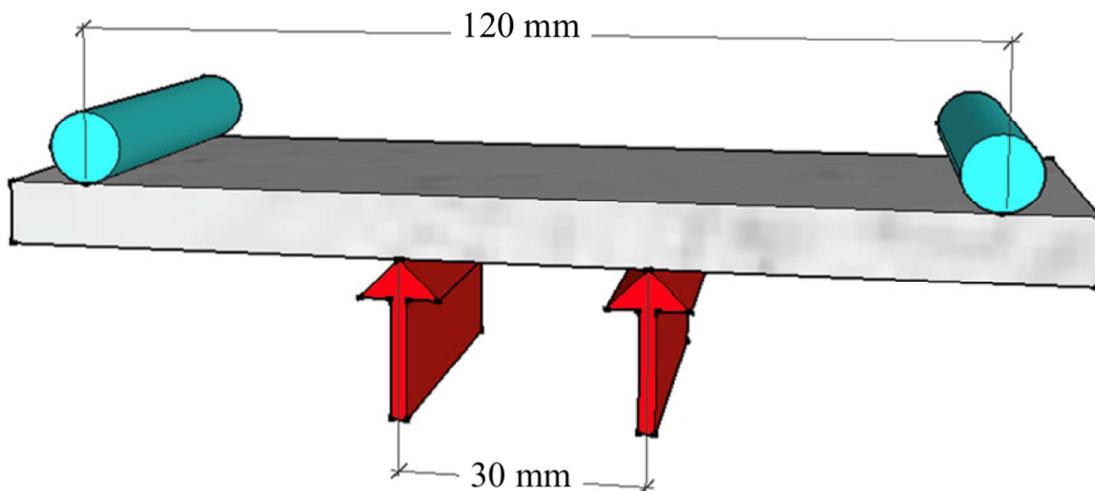
Figure 4 Position of printed reinforcement in Styrofoam mould.

189 The matrix materials were weighted according to the mix proportion given in Table 1. First,  
 190 solid ingredients were dry-mixed for four minutes in a Hobart laboratory mixer. After four  
 191 minutes, water and superplasticizer were added to the mixture and mixed for additional

192 four minutes. Subsequently, the materials were cast in the prepared moulds (with  
193 reinforcement already positioned) and vibrated for 30 seconds. Fresh specimens were  
194 covered with plastic sheets for one day (uniaxial tension) and two days (four-point  
195 bending), and then demoulded. After demoulding, they were placed in a curing room ( $20 \pm$   
196  $2^\circ\text{C}$ ,  $96 \pm 2\%\text{RH}$ ). Samples were cut to appropriate size for testing (described below) one day  
197 before testing.

#### 198 2.4. Four-point bending test

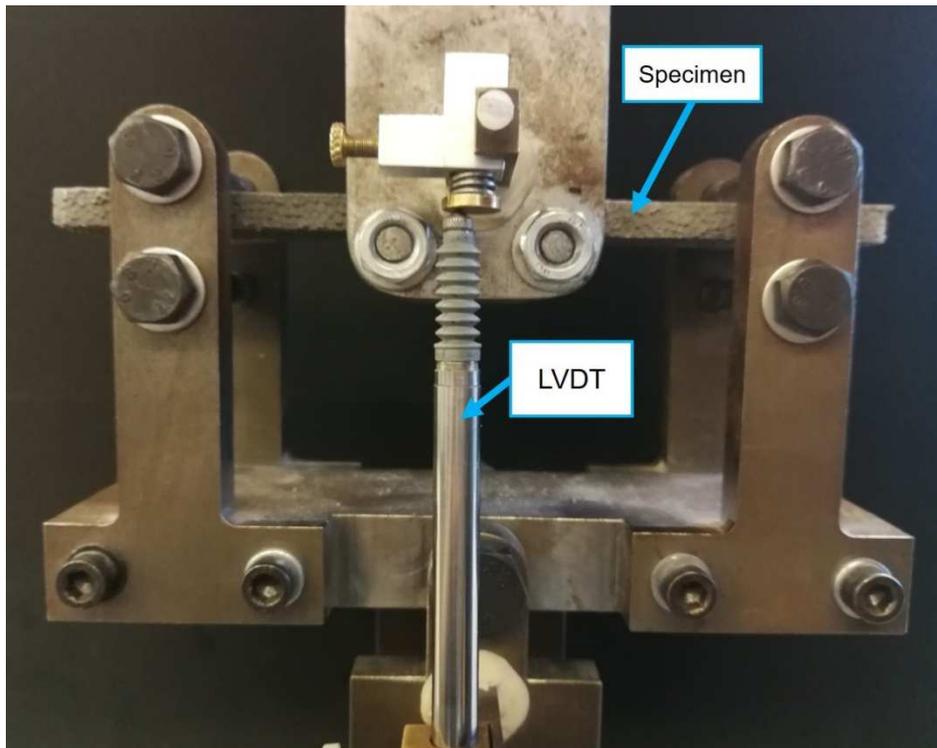
199 Four-point bending tests were performed on cured samples using a servo hydraulic press  
200 (INSTRON 8872) under displacement control with a constant rate of  $0.01\text{mm/s}$ . The load was  
201 measured by load cell and the deflection was measured by two linear variable differential  
202 transducers (LVDTs) placed at the mid-span. Specimen size used was  $180 \times 30 \times 8 \text{ mm}$ , with  
203 a loading span of  $120 \text{ mm}$  and loading applied as shown in Figure 5. A loaded specimen is  
204 shown in Figure 6. Note that the pattern given in Figure 2c was optimized for this loading  
205 setup: if a different loading setup were used, the middle region (i.e. the region with the  
206 maximum bending moment where a denser lattice mesh was printed) would have been  
207 different. For each specimen, flexural strength and flexural deflection capacity were  
208 determined as shown in Figure 7. For each configuration, at 7d four replicate specimens  
209 were tested and at 28d three replicate specimens were tested.



210  
211

Figure 5. Four-point bending test setup

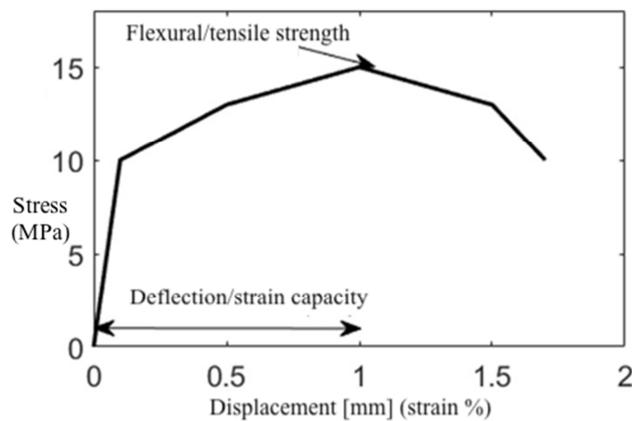
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213

214

Figure 6. Specimen loaded in four-point bending in the INSTRON 8872



215

216

217

Figure 7. Definition of flexural/tensile strength and flexural deflection capacity/strain capacity as determined by four-point bending/uniaxial tensile tests (adapted from [39])

## 218 2.5. Uniaxial tensile test

219 Similar to the four-point bending tests, uniaxial tensile tests were performed on cured

220 samples using a servo-hydraulic press (INSTRON 8872) under displacement control with a

221 constant rate of 0.005 mm/s. The load was measured by a load cell and the displacements

222 were measured by two linear variable differential transducers (LVDTs) placed on both sides

223 of the specimen. Prior to testing, specimens were glued with a mix of PLEX 7742F and

224 Pleximon on two parallel (non-rotating) steel plates. Specimen size used was 120 x 30 x 8

225 mm after cutting. The test is shown schematically in Figure 8. For each configuration, three  
226 replicate specimens were tested for reference (Ref) and large triangle patterns (LT and LT<sub>R</sub>),  
227 and four replicate specimens were tested for small triangle patterns (ST and ST<sub>28</sub>). During  
228 the uniaxial tensile test, a camera was placed in front of the specimen to capture photos of  
229 the cracking process. Afterwards, digital image correlation (DIC) analyses were performed  
230 to determine the strain field on the specimen surface during testing.

231 In order to obtain input parameters for ABS reinforcement needed for the lattice model,  
232 uniaxial tensile tests on printed ABS bars were also performed. The height and width of  
233 printed ABS bars was kept constant with the wall of a single cell of printed reinforcement  
234 meshes, namely 2 mm in width and 3 mm in height. The length of ABS bars was 100 mm. A  
235 same test setup as shown Figure 8 is used. Specimens for four-point bending and uniaxial  
236 tension is shown in Figure 9.

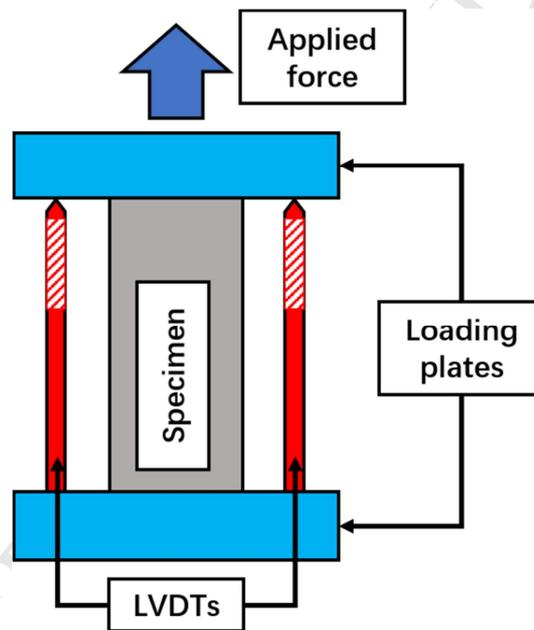


Figure 8. Schematic representation of the uniaxial tensile test on reinforced specimen.

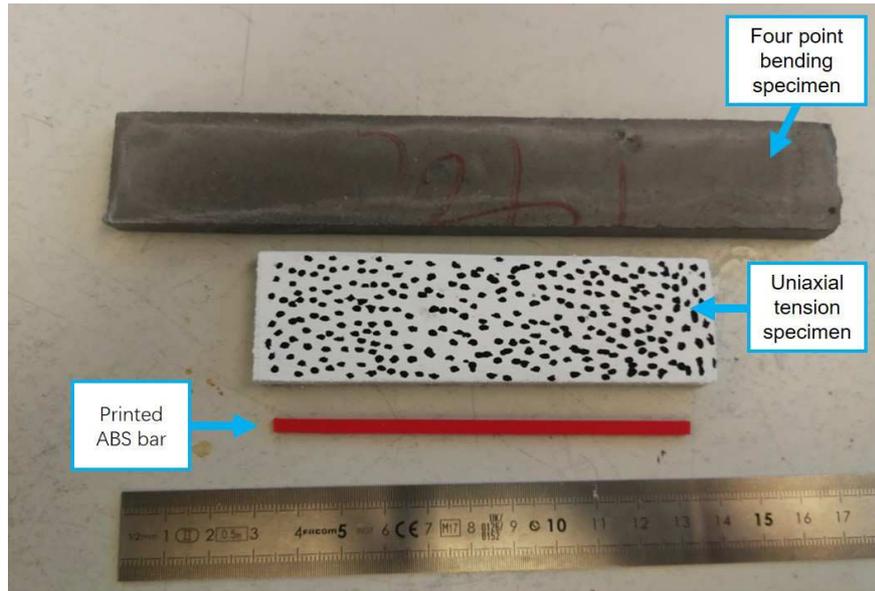


Figure 9 Specimens for four-point bending, uniaxial tension.

## 237 2.6. Lattice modeling

238 Numerical simulations of the deformation and fracture process during four-point bending  
 239 were carried out using the Delft lattice model. The following modelling procedure was  
 240 followed:

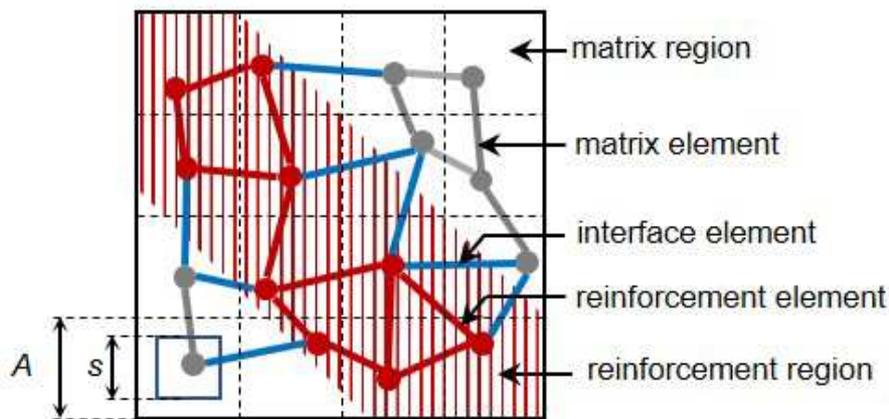
- 241 • A domain with the same size of the specimen (180 mm x 30 mm x 8mm) was generated  
 242 and divided into a grid of cubic cells with a 1x1x1 mm size.
- 243 • A node was generated at a random location in a sub cell of each grid. The ratio of the  
 244 size of sub cell ( $s$ ) and grid ( $A$ ) is defined as the randomness ( $R=s/A$ ) of the lattice  
 245 network. In this study  $R=0.99$  is used for all grids (as cementitious material is rather  
 246 heterogenous, a high randomness is necessary for simulating realistic cracking  
 247 patterns[40], for all simulated specimen the randomness is kept the same), only the  
 248 randomness of specimen surface was set to be  $R=0$  in order to apply load and support  
 249 evenly. The coordinates of a node in the domain were calculated by the following  
 250 equations.

$$\begin{aligned}
 x_i &= A * ((1-R) / 2 + R * a + i - 1) \\
 y_j &= A * ((1-R) / 2 + R * a + j - 1) \\
 z_k &= A * ((1-R) / 2 + R * a + k - 1)
 \end{aligned}
 \quad (1)$$

252 Where  $x, y, z$  is the coordinates of a node locating in the  $i$  th grid (integer from 1 to 181)  
 253 on  $x$  axis,  $j$  th grid (integer from 1 to 31) on  $y$  axis and  $k$  th grid (integer from 1 to 9) on  $z$

254 axis respectively;  $A$  is the grid size (see Figure 10);  $R$  is randomness ;  $a$  is a pseudo  
 255 random number ranging from 0~1 generated by MATLAB.

256 • Nodes in adjacent cells were then connected by beam lattice elements forming a  
 257 heterogenous rectangular lattice network representing the entire domain. In this sense,  
 258 the heterogeneity of cementitious materials was introduced. Depending on the  
 259 geometry of reinforced bars and position of the nodes, three categories of lattice  
 260 elements were generated: matrix elements, interface elements and reinforcement  
 261 elements. As shown in Figure 10, when an element has two nodes locating in matrix  
 262 region, it was defined as matrix element and similar criterion applies for defining  
 263 reinforcement element. When an element has two nodes located in different regions, it  
 264 was defined as an interface element. The generated lattice networks for the three  
 265 simulated cases are shown in Figure 11.



266

267

Figure 10. Schematics of domain discretization and element definition (shown in 2D for simplicity)

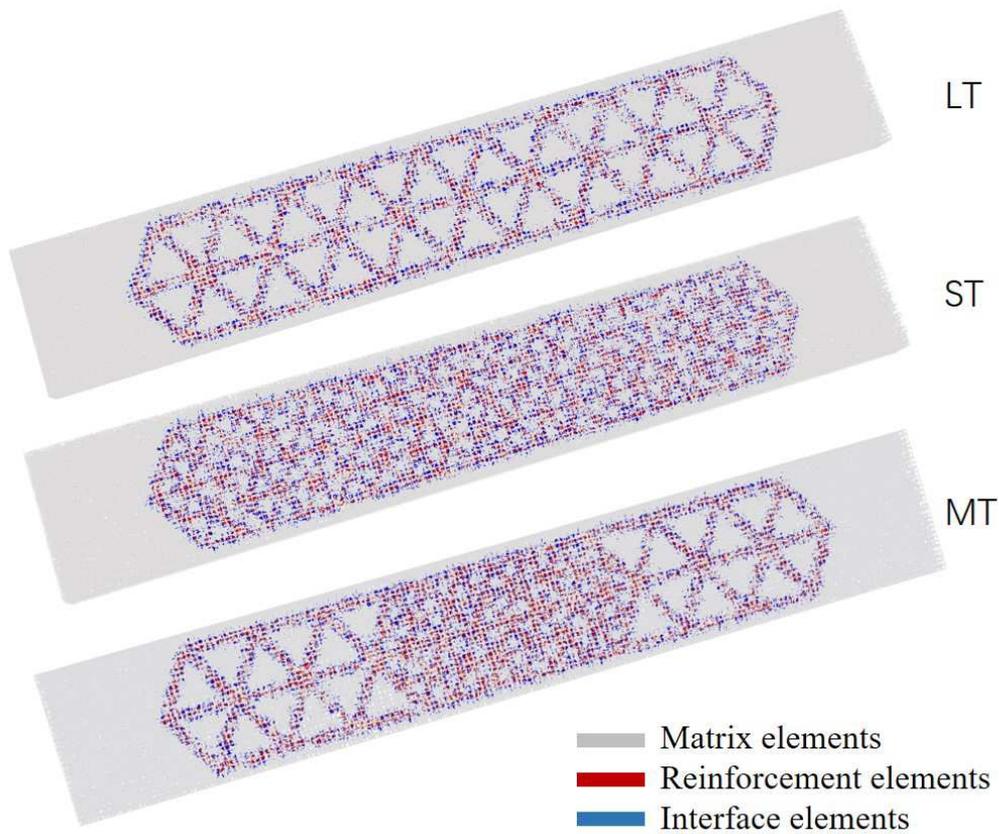


Figure 11 Lattice network of mortar bar reinforced by large triangles and small triangles.

268

269

- 270 • Linear elastic properties were assigned to the elements according their categories. A  
271 prescribed displacement boundary condition was imposed on the lattice network  
272 corresponding to the loading boundary condition and a set of linear elastic analyses  
273 were performed. In each step, the stress of every element was calculated and one critical  
274 element of which the stress exceeded the strength was removed from the lattice. Then,  
275 another linear analysis is performed, and this procedure is repeated until the entire  
276 lattice system fails. After the computing process, crack pattern and stress-deflection  
277 curve were extracted.

278 In order to obtain input mechanical properties for the lattice elements, several simulations  
279 were carried out first to fit reinforcement element properties and matrix element properties  
280 using the experiment results on ABS bars and the matrix. The interface element strength was  
281 assumed and the elastic modulus was assumed to be the mean value of the Voigt upper  
282 bound [40] (calculate by eq.2) and Reuss lower bound (calculate by eq.3) [40] for composites.

$$283 \quad E_I = V_m E_m + V_r E_r \quad (2)$$

$$\frac{1}{E_I} = \frac{V_m}{E_m} + \frac{V_r}{E_r} \quad (3)$$

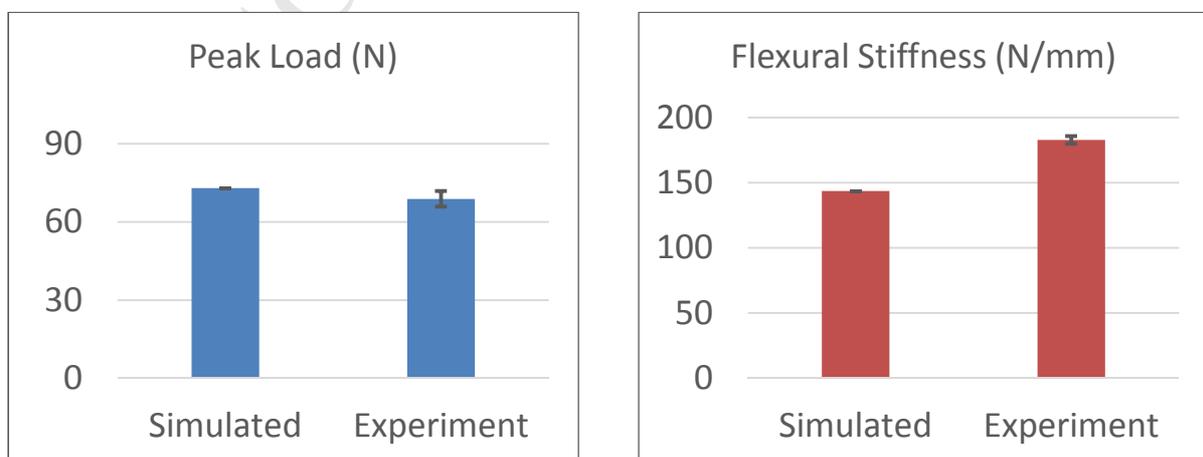
Where  $E_I$ ,  $E_m$  and  $E_r$  are the E-modulus of interface element, matrix element and reinforcement element respectively.  $V_m$  and  $V_r$  are the volume fraction of matrix and reinforcement in an interface element. As the lattice network has rather high randomness ( $R=0.99$ ),  $V_m = V_r = 0.5$  were assumed here for all interface elements.

During the fitting process, input parameters had been varied in the simulation of four-point bending tests on the matrix and uniaxial tensile tests on ABS bars until the simulated results is close to experiment results. The last input parameters were then adopted as inputs for the simulations of reinforced specimens. A comparison of fitting simulation results and experiments are shown in Figure 12, the simulated results are similar to experiment results. The input properties of the simulation are listed in Table 5. In this work, only four-point bending tests on LT, ST and MT at 7 days were simulated, as in the case of roughed surface much finer grids are required and in tension simulations multiple linear properties as described in [35] are required. Those simulations require too much computational resources, these tests were not simulated here.

Table 5. Input values for lattice model

Element	E-modulus (GPa)	$f_t$ (MPa)	$f_c$ (MPa)
Matrix	14.95	6	$-8^* f_t$
Reinforcement	1.59	35	$-2^* f_t$
Interface	5.57	0.1	$-8^* f_t$

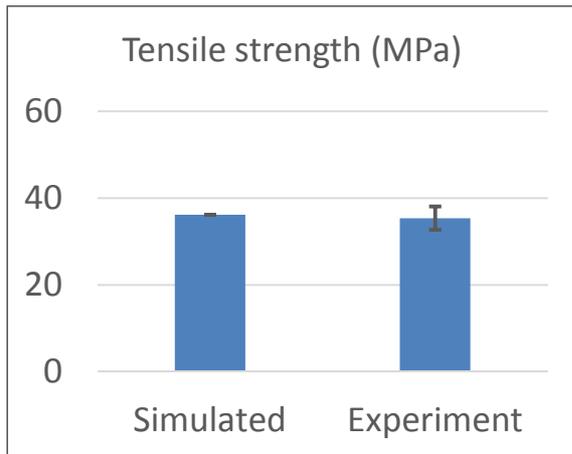
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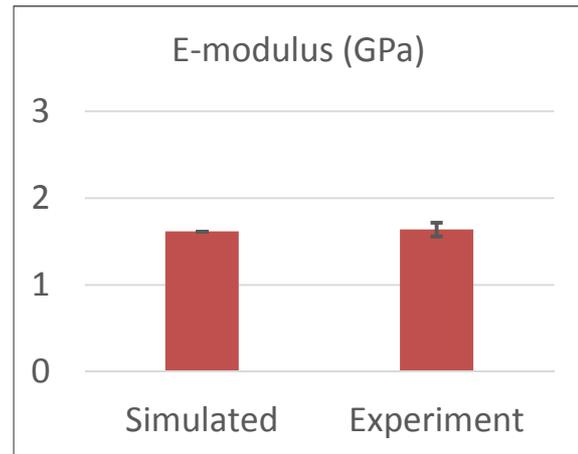
301

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(a)



(b)



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304

(c)

(d)

305 *Figure 12 Comparison of simulated values and experiment values of (a) flexural peak load of the matrix, (b) flexural stiffness*  
 306 *of the matrix in four-point bending tests, (c) Tensile strength of printed ABS bars, (d) E-modulus of printed ABS bars.*

### 307 3. Results and discussion

#### 308 3.1. Four-point bending tests

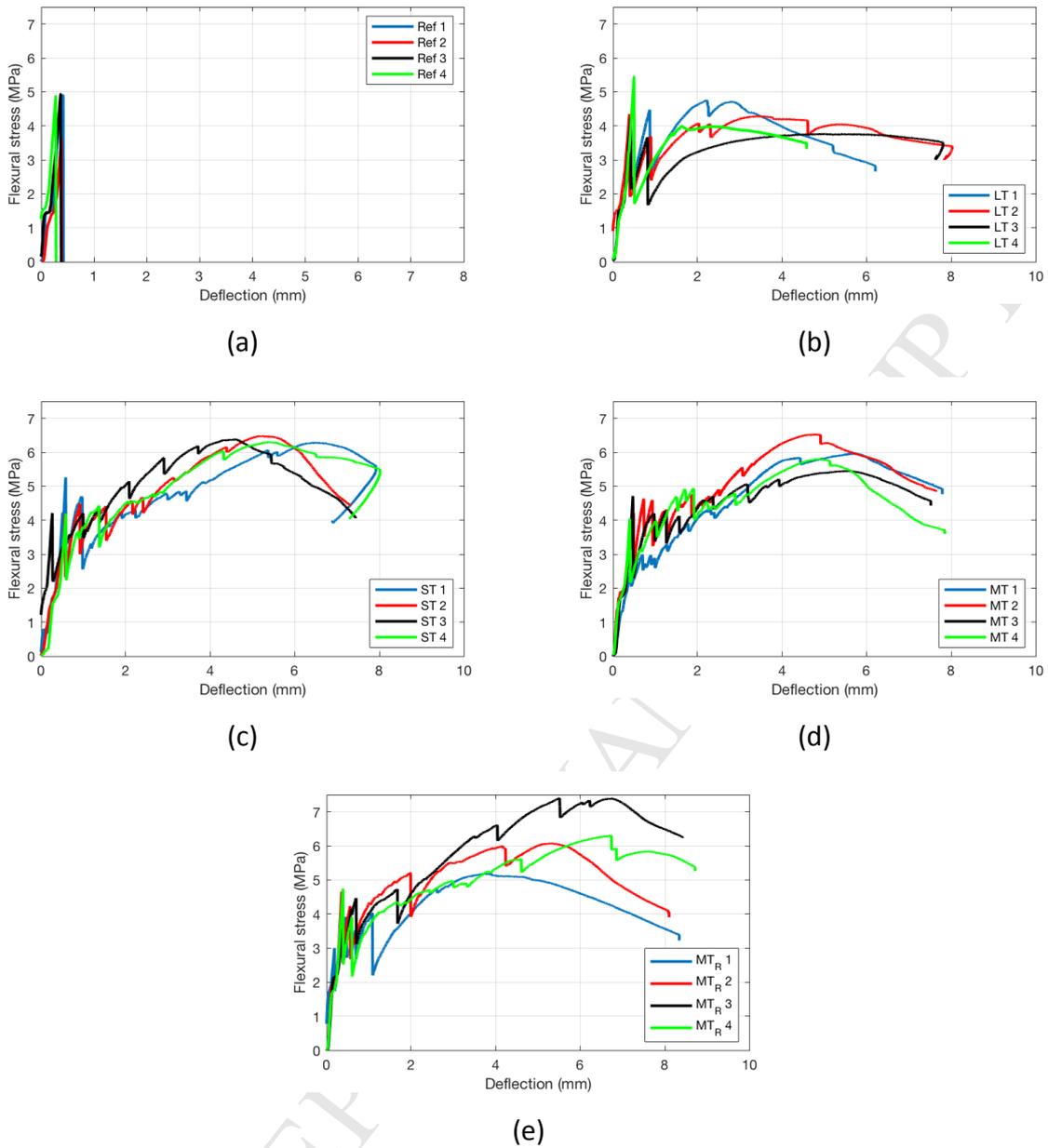
309 Flexural stress/deflection curves (average deflection measured by the two LVDTs) for all  
 310 tested specimens with different 3D printed polymeric reinforcement designs are given in  
 311 Figure 13 and Figure 14. A summary of the results is given in Table 6.

312 As expected, at 7d the reference specimens show brittle response with relatively low  
 313 deflection at failure (Figure 13a). On the other hand, all specimens reinforced with 3D  
 314 printed polymeric meshes can undertake appreciably higher deformation. Nevertheless,  
 315 there are significant differences between various reinforcement designs. Not all designs are  
 316 able to achieve the so-called deflection-hardening behavior, wherein the flexural strength is  
 317 higher than the first cracking strength. In that sense, looking at the average values given in  
 318 Table 6 may be misleading in some cases. For the LT pattern, the average flexural strength is  
 319 higher than the average of the first cracking strength. However, from Figure 13b it is clear  
 320 that not all LT specimens show deflection hardening behavior. In fact, only specimen LT 1  
 321 (shown in blue) shows deflection hardening behavior. In other specimens, although they do  
 322 not fail after the first crack occurs, the stress does not exceed the first cracking strength. In  
 323 essence, although large triangular reinforcement does provide these specimens with some  
 324 ductility, it cannot be used for obtaining (reliable) deflection hardening. In cementitious  
 325 materials such as e.g. SHCC, deflection hardening is typically achieved through multiple  
 326 cracking. Multiple cracking (witnessed by large drops in the stress/deflection diagrams) was

327 not observed in LT series, which mostly had only two cracks, typically close to the loading  
328 points (as shown in Figure 15). The ductility in this case was provided by the pullout of the  
329 polymeric reinforcement from the cementitious matrix. Note that a different matrix design  
330 could possibly result in deflection hardening even in this case, e.g. if a weaker matrix would  
331 have been used. This will be studied in the future.

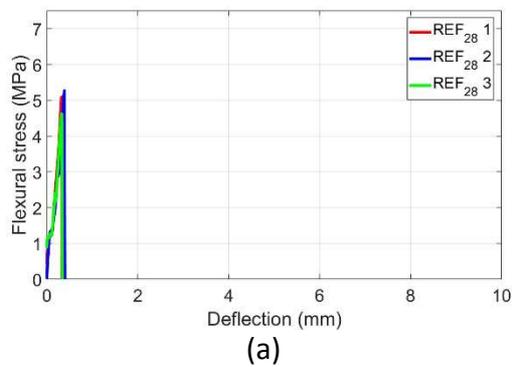
332 All specimens from other series showed a characteristic deflection hardening behavior. First,  
333 the 7d ST series (Figure 13c) showed deflection hardening achieved through multiple micro-  
334 cracking. Compared with the LT series, this is clearly an improvement. This was expected,  
335 however: similar to conventional fiber reinforced cementitious composites, more ductility is  
336 achieved with a higher percentage of fiber reinforcement. It is very interesting to note,  
337 however, as shown in Figure 13d that the MT (i.e. "functionally graded") series showed  
338 deflection hardening behavior as well, achieved through multiple micro-cracking (multiple  
339 cracks can be found in Figure 15). Again, in this series, the designed polymeric mesh was  
340 denser in the middle (constant moment region) than at the sides. This simple modification  
341 shows great potential of additive manufacturing: it is possible to achieve significant savings  
342 in the material if the reinforcement design is such that it is used only where needed (i.e.  
343 regions of high stress). This is something that cannot be achieved by conventional fiber  
344 reinforcement. The design with additively manufactured surface roughness (MT<sub>R</sub>) did not  
345 show markedly different behavior (Figure 13e) – deflection hardening was achieved in this  
346 case as well. It is possible that, if the cementitious matrix would have been weaker, surface  
347 roughness would have had a higher impact on the post-peak behavior. This will be further  
348 studied in the future.

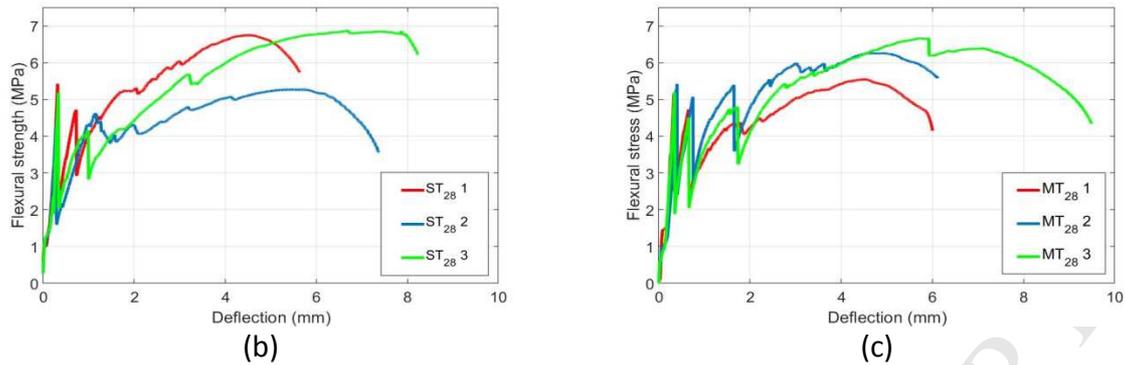
349 The two series at 28d of small triangles (ST<sub>28</sub>) and mixed triangles (MT<sub>28</sub>) were also tested,  
350 flexural stress-deflection curves are shown in Figure 14 . Normally, mortar bars with longer  
351 curing age are stronger and more brittle. This can also be found in Table 6 , the flexural  
352 strength of 28d specimen are higher and the strain capacity is lower. It could be even more  
353 difficult to have deflection hardening behavior for the reinforced mortar bars. However, as  
354 can be seen in Figure 14b and Figure 14c , both ST<sub>28</sub> series and MT<sub>28</sub> series still showed  
355 obvious deflection hardening behavior.



356  
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Figure 13. Flexural stress-deflection curves for 7d specimens tested in bending. (a) reference (no reinforcement); (b) large triangles (LT); (c) small triangles (ST); (d) mixed triangles (MT); (e) mixed triangles with a rough surface (MT<sub>R</sub>).



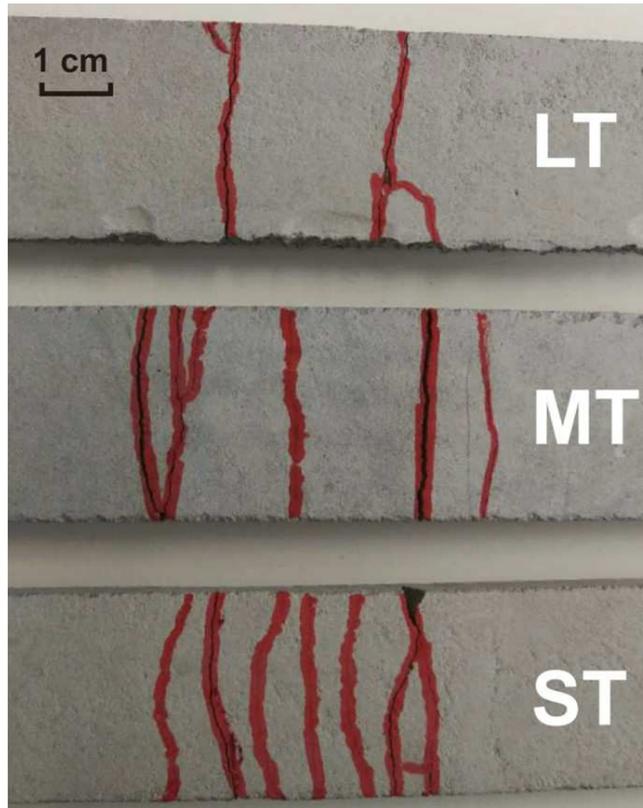


358 Figure 14 Flexural stress-deflection curves for 28d specimens tested in 4-point bending. (a) reference (no reinforcement); (b)  
 359 small triangles ( $ST_{28}$ ); (c) mixed triangles ( $MT_{28}$ ).

360  
 361 Table 6. A summary of four-point bending results

Series	First cracking strength (Standard deviation) [MPa]	Flexural strength (Standard deviation) [MPa]	Deflection capacity (standard deviation) [mm]
Ref	4.584 (0.549)	4.584 (0.549)	0.361 (0.052)
LT	4.514 (0.546)	4.693 (0.472)	0.944 (0.881)
ST	4.308 (0.606)	6.127 (0.337)	5.429 (0.675)
MT	4.321 (0.666)	6.002 (0.541)	5.312 (0.605)
MT <sub>R</sub>	4.255 (0.712)	6.243 (0.784)	5.369 (1.010)
Ref <sub>28</sub>	4.992 (0.337)	4.992 (0.337)	0.343 (0.036)
ST <sub>28</sub>	4.973 (0.583)	6.298 (0.890)	5.545 (1.012)
MT <sub>28</sub>	5.255 (0.147)	6.162 (0.569)	4.985 (0.661)

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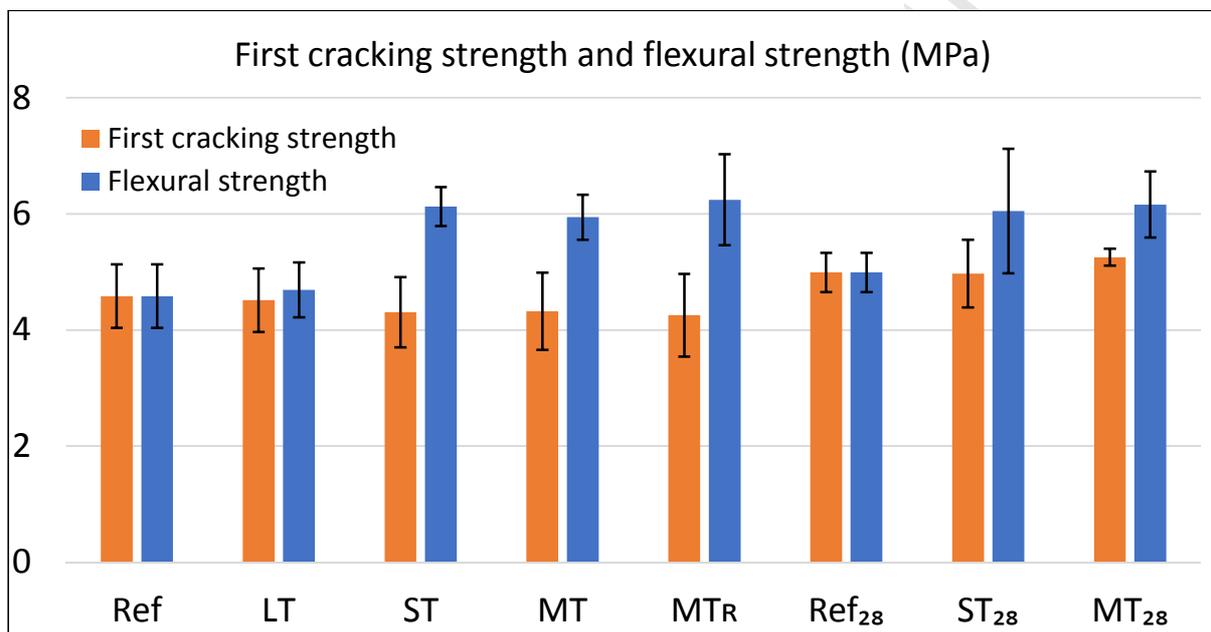


363  
364 *Figure 15 Highlighted cracks in the middle region of specimens with larger triangles (LT), mixed triangles (MT) and small*  
365 *triangles (ST), respectively, after the four-point bending test.*

366 In Figure 16-Figure 17, the reinforced specimens and reference specimens are compared in  
367 terms of the first cracking strength, flexural strength, and deflection capacity for different  
368 specimen series. From Figure 16, it can be seen that the first cracking strength is not  
369 obviously affected when printed mesh is used in all experimental series of the same age. The  
370 highest difference between the reinforced specimens and reference is 7.2% (between Ref and  
371  $MT_R$ ) at 7d and 5.3% (between  $Ref_{28}$  and  $MT_{28}$ ) at 28d. However, while the LT series doesn't  
372 show an obvious increase in average flexural strength compared to the reference (increase is  
373 less than 2.5%), other series show a significantly increased flexural strength (33.7%, 30.9%  
374 and 36.2% for the ST, MT, and  $MT_R$  series, respectively). Similar increase in flexural strength  
375 at 28d can also be found: 26.2% and 23.4% for  $ST_{28}$  and  $MT_{28}$  respectively. The increase in the  
376 flexural strength is a result of deflection hardening in these series. The most important  
377 difference between different series is the flexural deflection capacity (Figure 17). While the  
378 LT specimen series shows only a slightly higher average flexural deflection capacity  
379 compared to the reference (and only due to the one specimen which did exhibit deflection  
380 hardening), other tested series ST, MT,  $MT_R$ ,  $ST_{28}$  and  $MT_{28}$  all show significantly improved  
381 flexural deflection capacity. It is rather interesting that at 7d and 28d, small triangle series

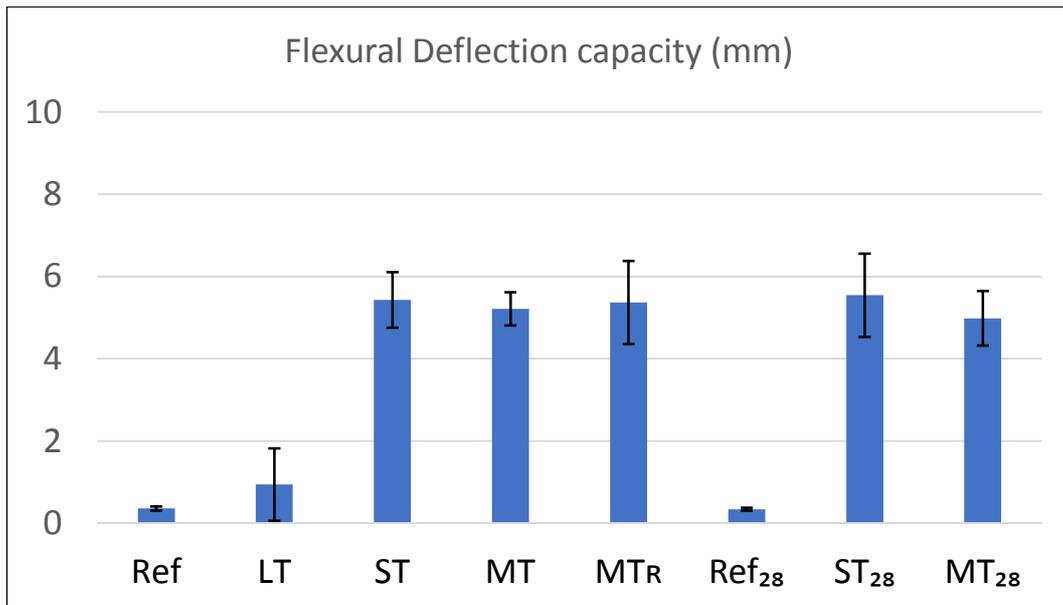
382 (ST and ST<sub>28</sub>) and mixed series (MT, MT<sub>R</sub> and MT<sub>28</sub>) show quite similar increased flexural  
 383 deflection capacity comparing to reference: at 7d, 1403% (ST), 1345% (MT) and 1387% (MT<sub>R</sub>).  
 384 At 28d, they are 1516% (ST<sub>28</sub>) and 1353% (MT<sub>28</sub>). This is an additional proof that, with  
 385 additive manufacturing of reinforcement, there is potential for creating functionally graded  
 386 cementitious composites and thereby optimizing material usage. Additionally, MT<sub>R</sub> and MT  
 387 have quite similar flexural strength and deflection capacity. Comparing to flat surface  
 388 designs, the rough surface design did not provide the reinforced mortar bars with any  
 389 additional ductility in the performed tests.

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 393

Figure 16. Comparison of first cracking strength and flexural strength of specimens tested in four-point bending (standard deviation is indicated).



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Figure 17. Flexural deflection capacity of specimens tested in four-point bending (standard deviation is indicated).

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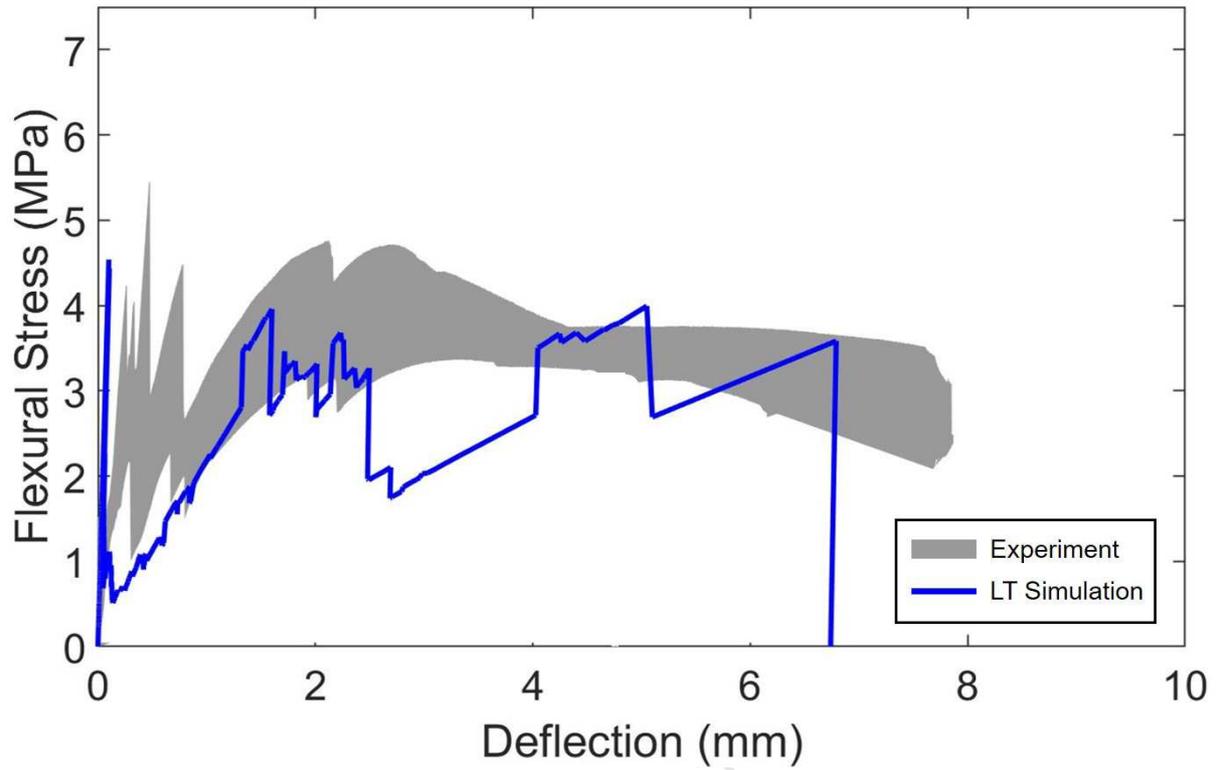
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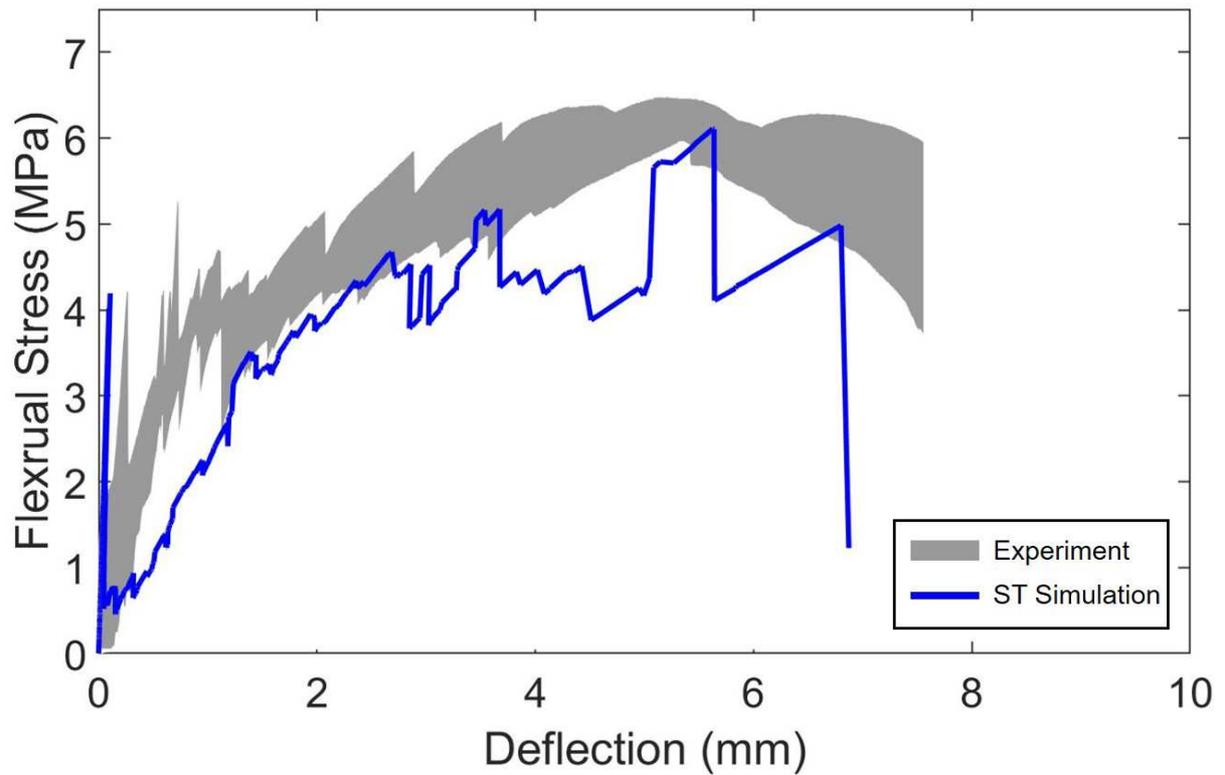
Correspondingly, as can be seen in Figure 18, the simulated curves of LT and ST both show good agreement with experiments. For LT (shown in Figure 18a), after the first peak the reinforcement took over the load and stress increased again while the stress is always lower than the first peak until the specimen failed, deflection hardening behavior was not achieved. Although ductility of the specimen was increased from the simulated flexural stress-deflection curve, only two main cracks can be seen from the fractured specimen (shown in Figure 19a), which resembles the cracking pattern obtained from the experiment (Figure 15). For ST and MT, the simulated stress-deflection also corresponds to the experiment (shown in Figure 18b and Figure 18c). After the first crack, the stress increased and was higher than the first peak until failure. Multiple cracking behavior can be observed from the cracking history (shown in Figure 19b and Figure 19c).



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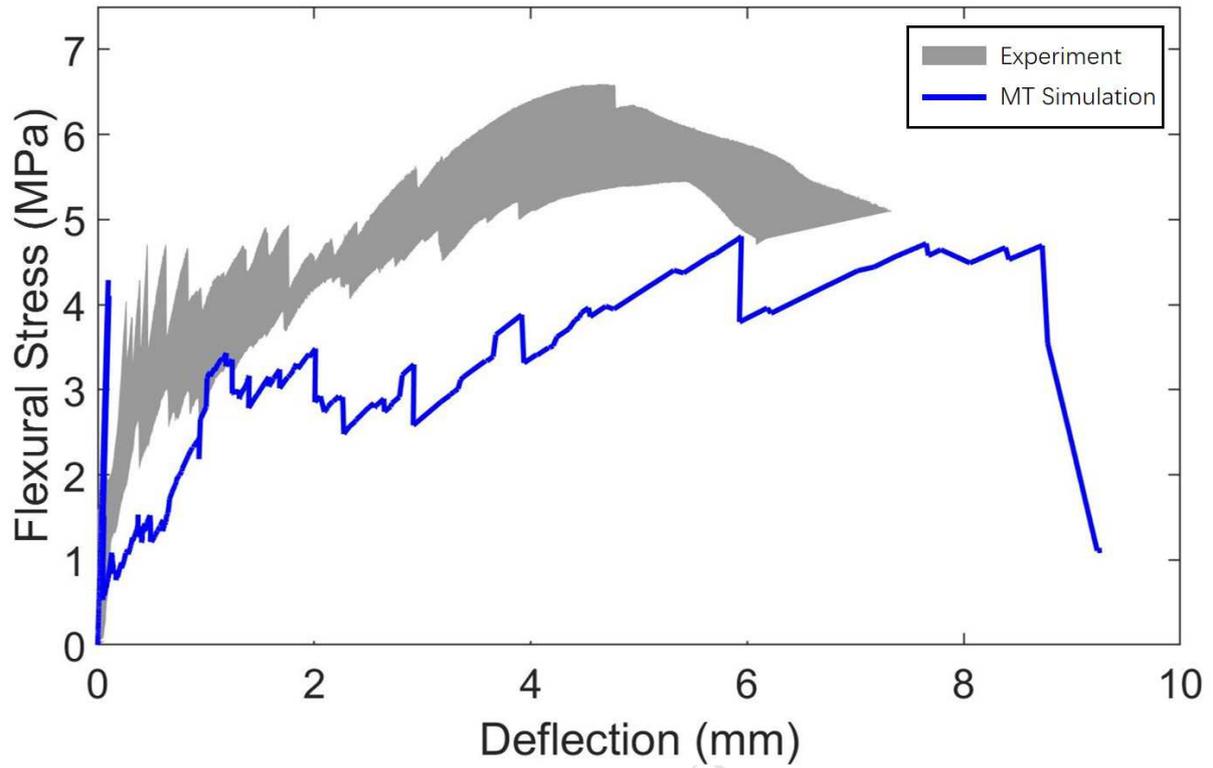
(a)



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(b)



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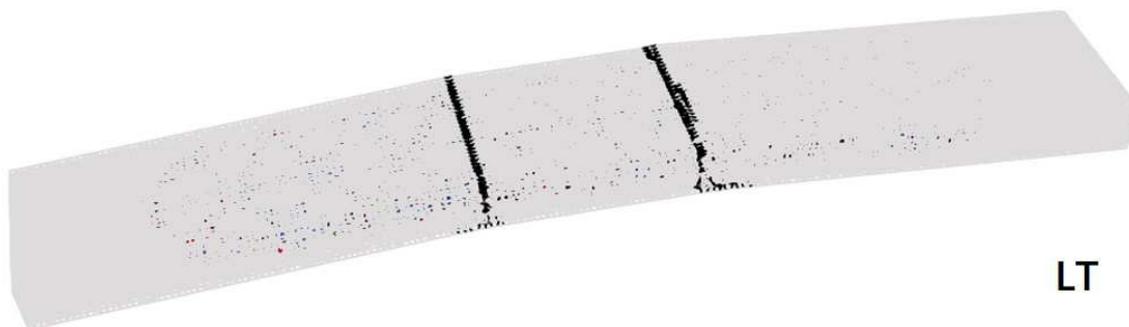
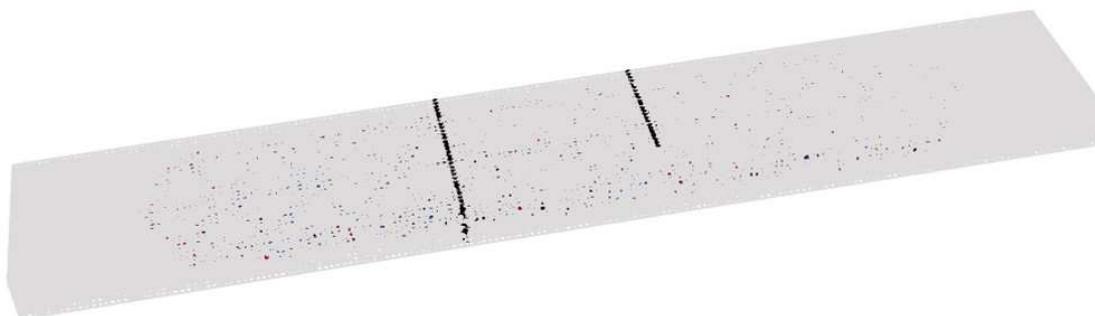
(c)

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Figure 18 Comparison of experiment results and simulation results of four-point bending tests on mortar bars reinforced by (a) large triangles and (b) small triangles.

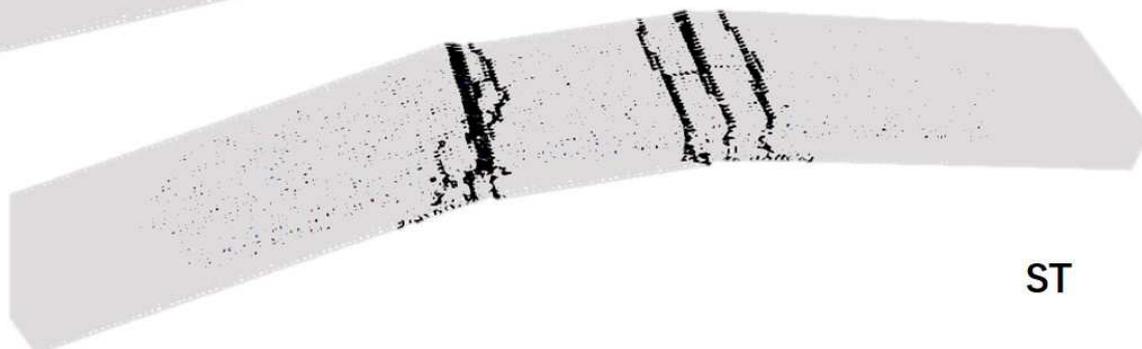
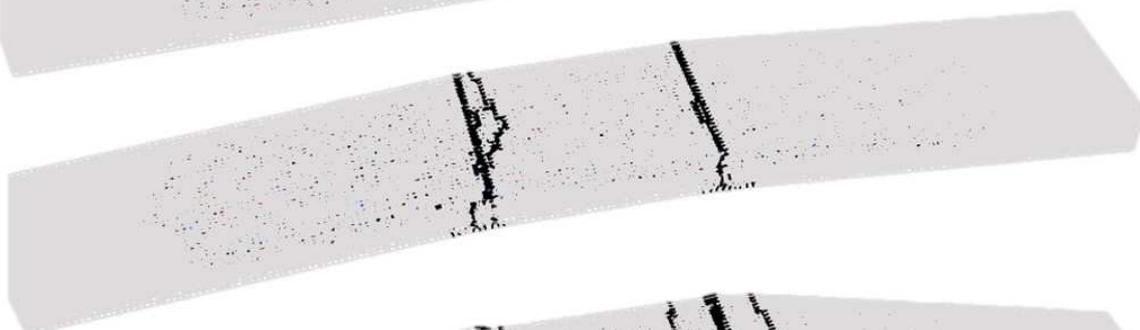
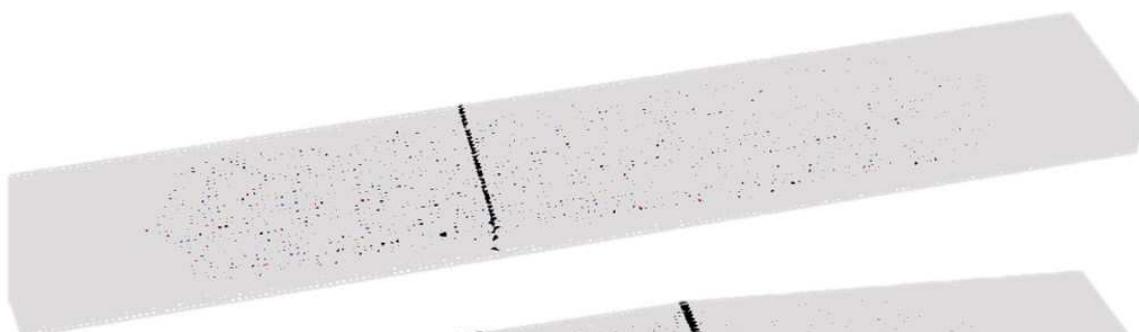
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LT

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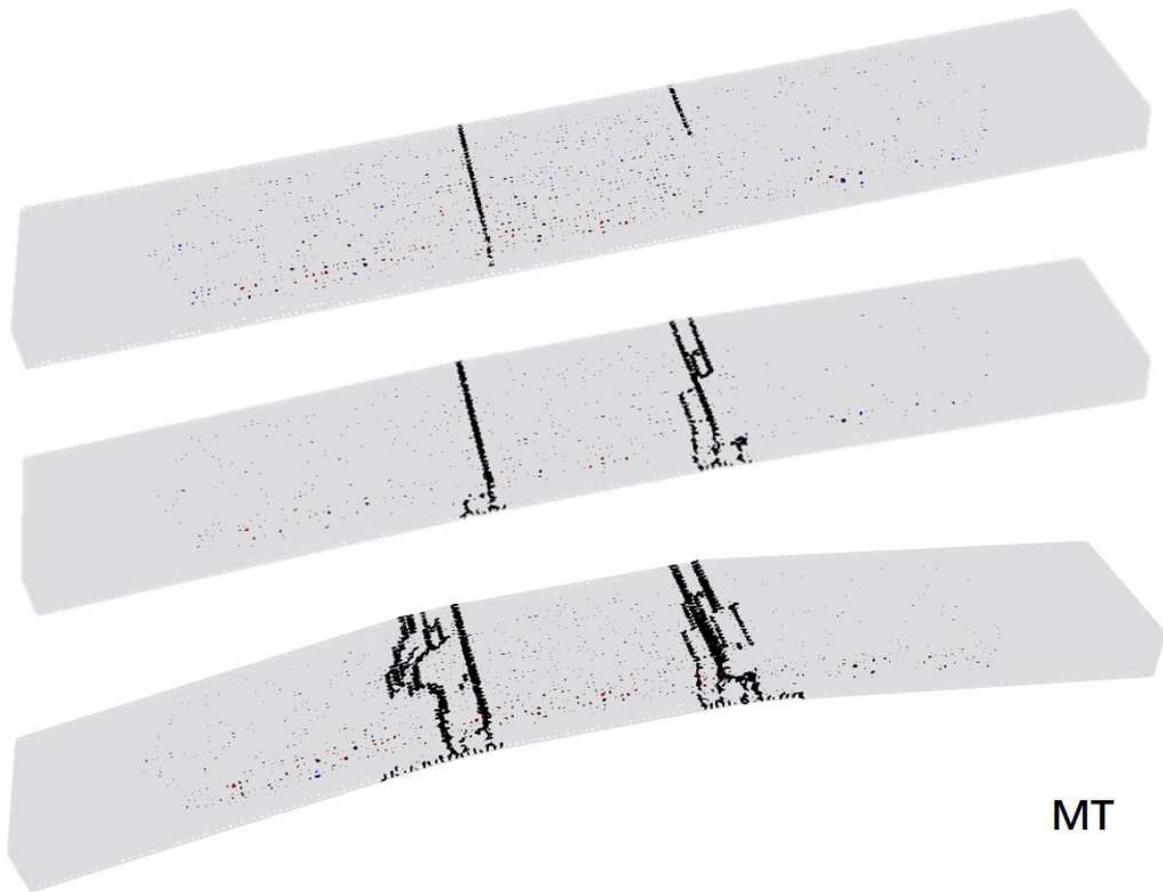
(a)



ST

418  
419

(b)



(c)

Figure 19 Simulated cracking history of (a) 7d large triangles, (b) 7d small triangles (ST) and (c) 7d mixed triangles (MT), black elements are failed elements.

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### 424 3.2. Uniaxial tension tests

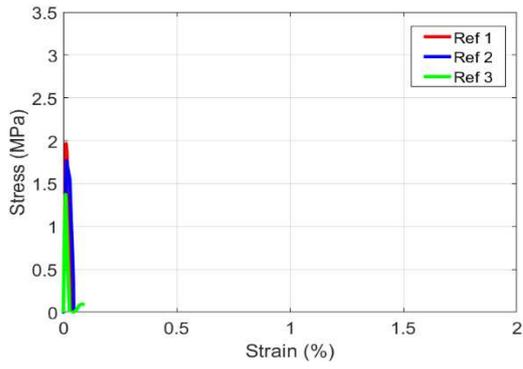
425 Uniaxial stress/strain curves (average strain measured by the two LVDTs) for all tested  
426 specimens reinforced by 3D printed polymeric meshes with different patterns are given in  
427 Figure 20. A summary of the results is given in Table 7. It is clear that the reference specimen  
428 (i.e. the one without polymeric reinforcement) exhibits brittle behavior in tension (Figure  
429 20a), which is typical of cementitious materials [41]. It has a low strain capacity and only a  
430 single crack formed. On the other hand, all specimens reinforced with 3D printed polymeric  
431 meshes are capable of undertaking larger strains. Furthermore, as can be seen from Figure  
432 20, in tension all tested reinforced specimens of various configurations did show strain  
433 hardening behavior: after the first cracking, all reinforced specimens were able to carry  
434 increasing amounts of stress until the maximum stress was reached. Still, different behaviors  
435 of reinforced specimens are obvious within varied reinforcement patterns.

436 The large triangle patterns (LT and LT<sub>R</sub>) exhibit quite similar strain hardening behavior:  
437 after cracking, only a few cracks formed before the ultimate strain was reached. The stain

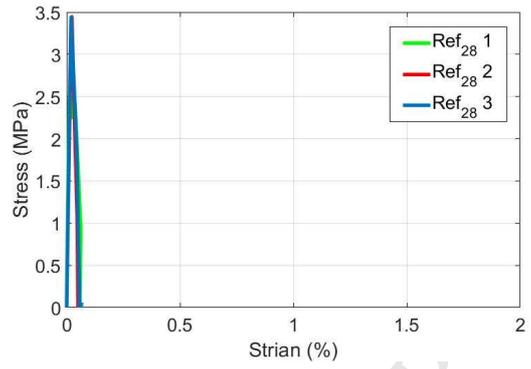
438 hardening behavior occurred mainly not from multiple cracking mechanism but the so  
439 called slip hardening behavior [35] - namely the friction between the reinforcement and the  
440 matrix which resists the slippage. In the observed case, the friction is sufficient to result in  
441 slip hardening behavior, providing the L<sub>TR</sub> and LT with overall higher strain capacity. As  
442 the roughed surface provides higher friction (rough surface has more contacting area  
443 between matrix and reinforcement), the strain capacity of L<sub>TR</sub> series (0.741%) is slightly  
444 higher than LT series (0.503%).

445 Comparing to the large triangle patterns, the multiple cracking behavior of specimens  
446 reinforced with small triangles (ST and ST<sub>28</sub> series) is much more obvious which is similar to  
447 the typical strain hardening behavior of e.g. SHCC [17, 18] or TRC [24, 25]. In most  
448 specimens in ST and ST<sub>28</sub> series, numerous drops in the stress-strain curve indicate multiple  
449 cracks forming in the loading process. Finally, after the maximum stress is reached, the  
450 specimen fails in a similar manner to LT specimens, i.e. through pullout of the polymeric  
451 reinforcement and localization of a single wide crack. It is interesting to observe that in ST  
452 series (Figure 20), results of all specimens are quite constant, only in the final pulling out  
453 stage, two specimens (ST 2 and ST 4) behave differently than other specimens in the final  
454 pull out stage: instead of being pulled out at the final drop, the printed meshes were  
455 suddenly ruptured in tension (sudden drop of the last peak) which resulted in relatively  
456 higher strain capacity and flexural strength.

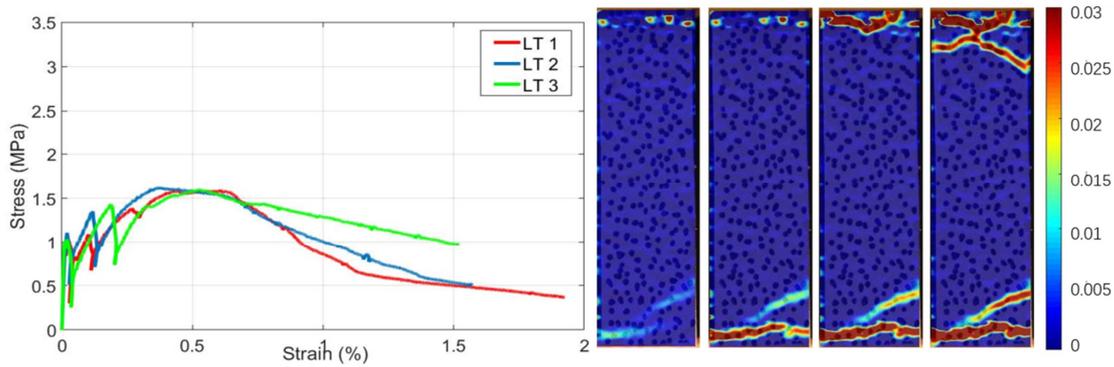
457 In previous section, the flexural strength of 28d reference specimens are slightly stronger  
458 than 7d reference specimens. However, in tension the influence of curing age on the tensile  
459 strength of the matrix is considerable. From Table 7, tensile strength of the reference series at  
460 28d (3.444 MPa) is much higher than that of reference series at 7d (1.705 MPa) and  
461 consequently, the stain capacity of ST<sub>28</sub> series (0.579%) is much lower than ST series  
462 (1.135%).



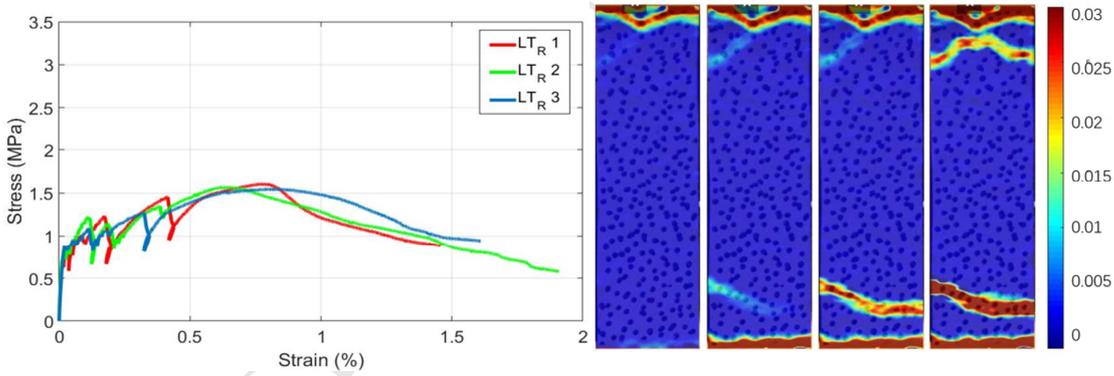
(a)



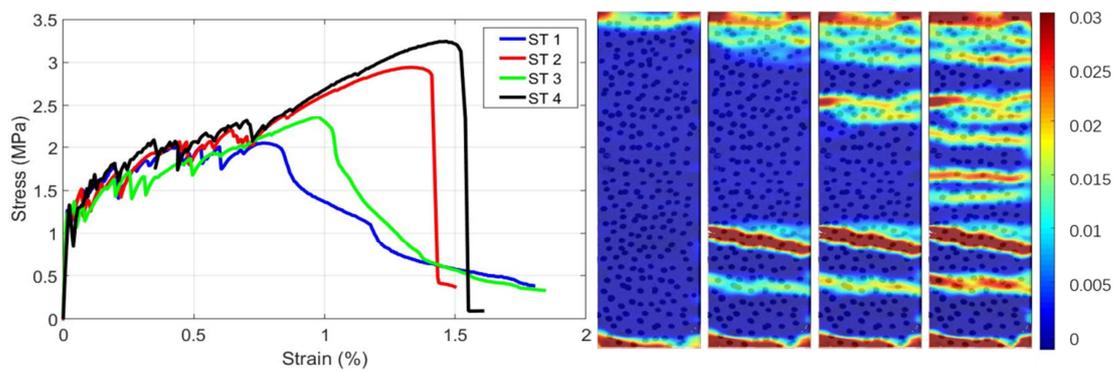
(b)



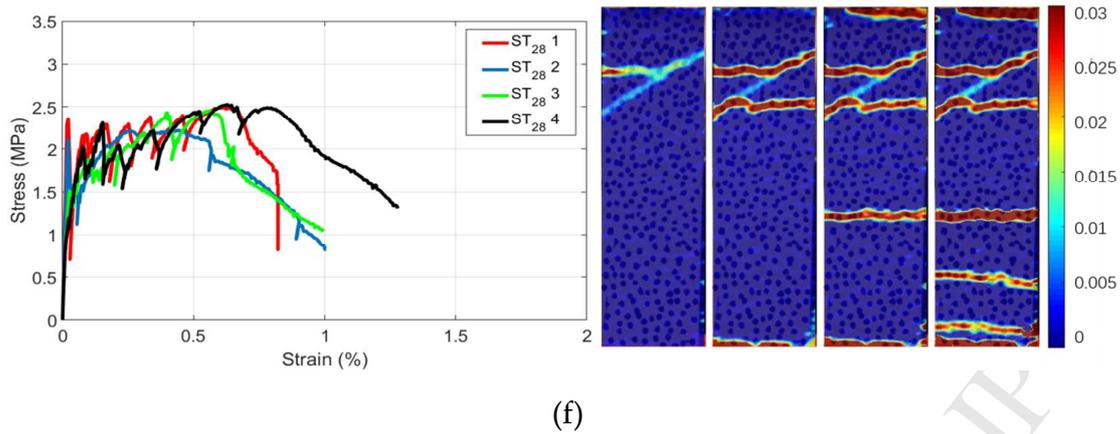
(c)



(d)



(e)



463

464 Figure 20. Tensile stress-strain curves and corresponding DIC results for specimens reinforced with different 3D printed  
 465 polymeric meshes. (a) reference (no reinforcement) at 7d; (b) reference (no reinforcement) at 28d; (c) large triangles at 7d  
 466 (LT); (d) large triangles with a rough surface at 7d (LT<sub>R</sub>); (e) small triangles at 7d (ST); (f) small triangles at 28d (ST<sub>28</sub>).

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468 Table 7. A summary of uniaxial tension results

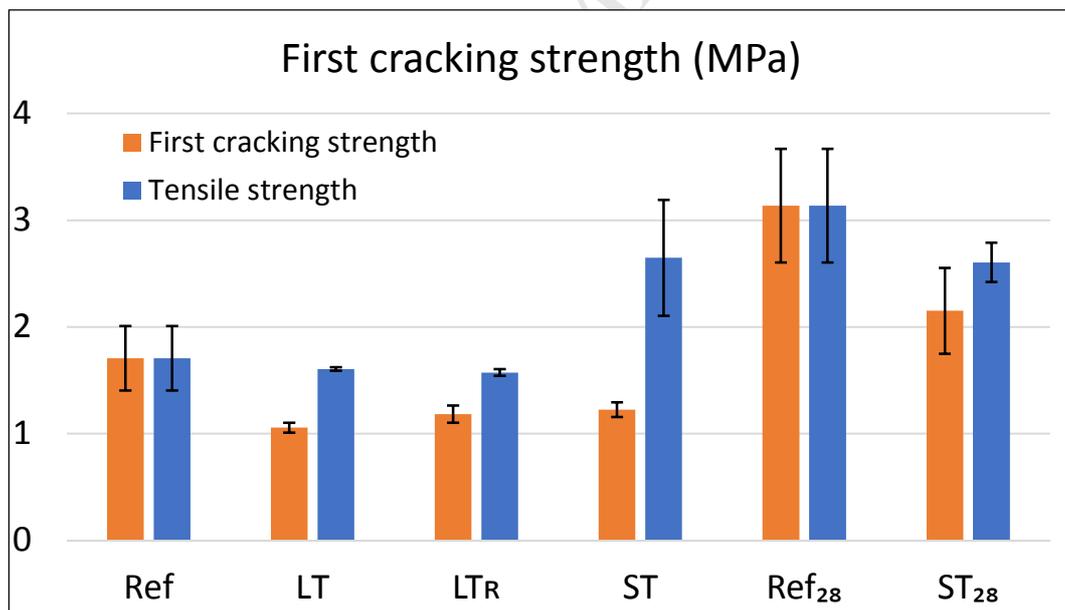
Series	First cracking strength (Standard deviation) [MPa]	Tensile strength (Standard deviation) [MPa]	Strain capacity (standard deviation) [%]
Ref	1.705 (0.302)	1.705 (0.302)	0.012 (0.002)
LT	0.944 (0.051)	1.604 (0.017)	0.503 (0.120)
LT <sub>R</sub>	0.784 (0.087)	1.572 (0.030)	0.741 (0.111)
ST	1.223 (0.070)	2.647 (0.543)	1.135 (0.323)
Ref-28d	3.136 (0.533)	3.136 (0.533)	0.021 (0.002)
ST-28d	1.093 (0.181)	2.424 (0.140)	0.579 (0.095)

469

470 Figure 21 provides a comparison between correlated first cracking strength (first cracking  
 471 strength divided by cross sectional reinforcing ratio) and tensile strength of different series.

472 As can be seen in Figure 21, all reinforced specimens show significant improvement  
 473 compared to the first cracking strength which is a result of strain hardening in these  
 474 materials. In uniaxial tension tests, because part of the cross section is replaced by the  
 475 printed mesh in reinforced specimen, the real cross section area of the matrix is smaller than  
 476 that of the reference specimen, which resulted in lower calculated first cracking strength in  
 477 reinforced series. In this sense, the matrix cracking strength is correlated according to the

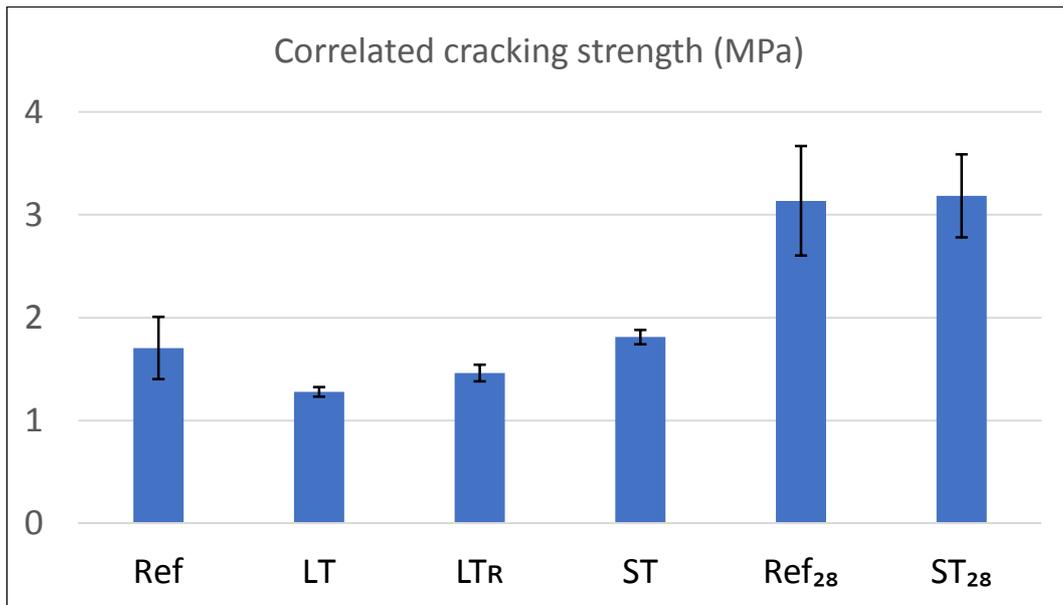
478 first cracking strength and the highest cross-sectional reinforcing ratio from Table 3 of each  
 479 pattern. As shown in Figure 22, considering the deviation, there is no significant difference  
 480 between the reinforced test series and reference specimens in correlated cracking strength of  
 481 the matrix. Still, in LT series the correlated first cracking strength is relatively lower. This  
 482 could be the fact that printed reinforcement might introduce many interfacial zones between  
 483 the matrix and the reinforcement making the crack easier to initiate in the reinforced  
 484 specimens. Furthermore, matrix compaction is somewhat more difficult in the reinforced  
 485 series due to the spacing regions of the printed reinforcement, possibly causing more  
 486 imperfections to form in some of the specimens compared to the reference series.  
 487 Even more significant improvements can be seen in terms of tensile strain capacity (Figure  
 488 23): the tensile strain capacity is increased by 4540%, 6750%, and 6600% compared to the  
 489 reference series the LT, ST and LTR series, respectively. Even with a simple reinforcement  
 490 mesh design used in this preliminary work, these are significant improvements. Clearly,  
 491 there is still room for improvement. This indicates a huge potential that additive  
 492 manufacturing has in creating strain hardening cementitious composites.



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Figure 21. First cracking strength and Tensile strength of specimens tested in tension (standard deviation is indicated).

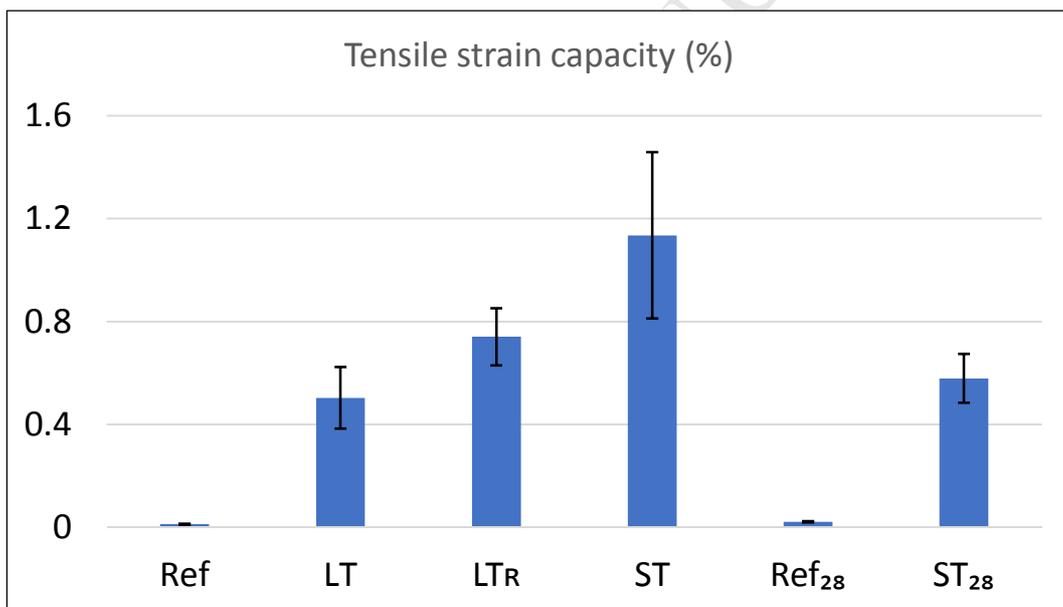


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Figure 22 Correlated cracking strength of the matrix (standard deviation is indicated)



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Figure 23. Tensile strain capacity of specimens tested in tension (standard deviation is indicated).

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#### 4. Conclusions

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In this work, a preliminary study of using additively manufactured polymeric meshes as reinforcement for creating strain hardening cementitious composites. Simple reinforcement meshes were designed, manufactured, and tested in four-point bending and uniaxial tension. In addition, four-point bending tests were simulated using the lattice model. Based on the performed experiments and simulations, the following conclusions can be drawn:

- 506 ○ Certain designs of 3D printed polymeric meshes enable creating composites with  
507 strain hardening and deflection hardening behavior. This mainly depends on the  
508 mesh design in terms of a same matrix.
- 509 ○ Use of 3D printed polymeric reinforcement enables significantly increasing the  
510 deflection and tensile strain capacity of cementitious composites compared to the  
511 reference material.
- 512 ○ According to experimental results, deflection hardening was observed only in  
513 specimens which showed multiple cracking. Other specimens (in which pullout of  
514 the reinforcement was the only mechanism) did show increased ductility compared  
515 to the reference, but no significant hardening was observed.
- 516 ○ Numerical simulation results show good agreement with the experiment, specimen  
517 reinforced by finer mesh (ST) and mixed mesh (MT) show multiple cracking  
518 behavior and deflection hardening was obtained while specimen reinforced by  
519 coarser mesh (LT) didn't show multiple cracking and deflection hardening.
- 520 ○ Strain hardening was observed in all designs of polymeric reinforcement tested.  
521 Unlike the case of bending, this is valid for both those exhibiting multiple cracking  
522 and those wherein reinforcement slip is the main mechanism observed.
- 523 ○ In four-point bending, a simple mesh pattern (MT) showed great potential of using  
524 additive manufacturing for creating functionally graded cementitious composites.
- 525 ○ Surface roughness designed and created by the additive manufacturing process can  
526 be used as an additional option for creating strain hardening cementitious  
527 composites by manipulating the bond between the polymeric mesh and the  
528 cementitious matrix.

529 Although this research shows great potential of the proposed approach, there are still many  
530 issues that need to be studied. First, in this research, the focus was on the mesh design,  
531 while the cementitious matrix was kept constant. It should be noted, however, that the  
532 behavior of the composite does not depend only on the design of the reinforcement, but also  
533 on the matrix properties [42]. In this research, a matrix with rather low w/b ratio (0.33, Table  
534 1) was used, resulting in a relatively strong material after 28 days. It is possible that even  
535 higher deflection and strain capacity could be obtained with lower w/b ratio. Furthermore,  
536 no detailed knowledge of the bond behavior between the 3D printed polymeric

537 reinforcement and the cementitious matrix is available at present. In this research, this  
 538 parameter has been changed only by manipulating the physical bond through creating  
 539 surface roughness in some cases. Other possible treatments, such as e.g. coating of  
 540 reinforcement to improve the chemical bond, have not been studied. This will be a part of  
 541 future research. Finally, printing parameters of 3D printing were kept constant in this  
 542 research. These parameters may significantly influence the properties of the printed  
 543 reinforcement. This also needs to be investigated further in the future.

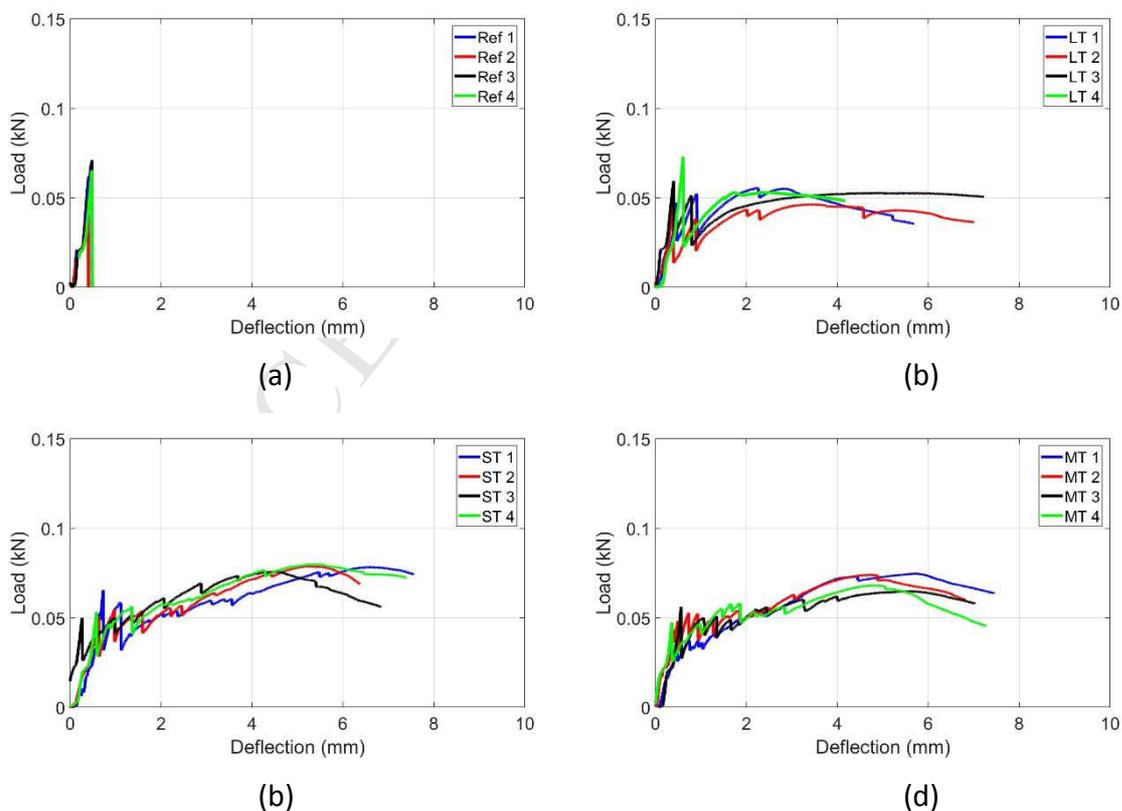
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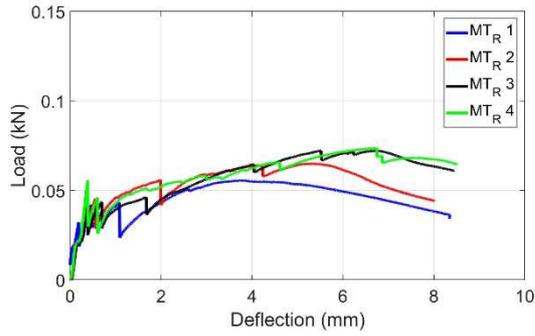
## 545 Acknowledgements

546 Yading Xu would like to acknowledge the funding supported by China Scholarship Council  
 547 (CSC) under the grant CSC No.201708110187. The authors would like to acknowledge Mr.  
 548 Vincent Huigen, Mr. Jorgi Penners and Mr. Bas Berger for their help in the sample preparing  
 549 and mechanical tests.

## 550 Appendix

551 Load-Deflection curves of 7 days four-point bending tests are shown in Figure A.1.





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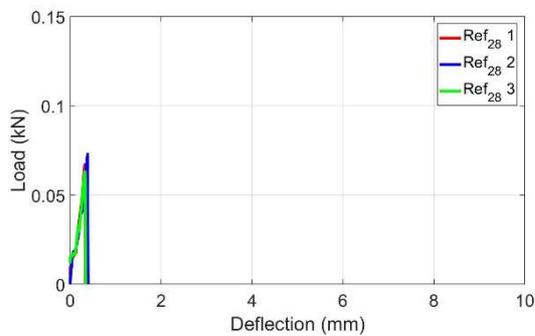
557

(e)

558 *Figure A.1 Load-deflection curves of 7 days specimen. (a) reference (no reinforcement); (b) large triangles (LT); (c) small*559 *triangles (ST); (d) mixed triangles (MT); (e) mixed triangles with a rough surface (MTR).*

560 Load-Deflection curves of 28 days four-point bending tests are shown in Figure A.2.

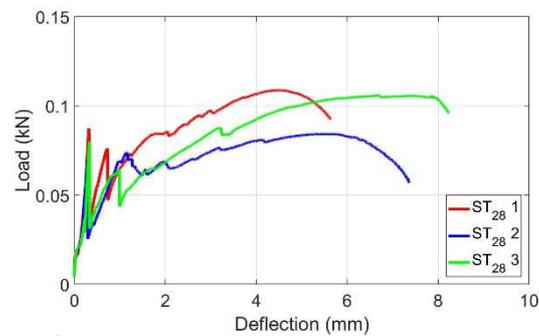
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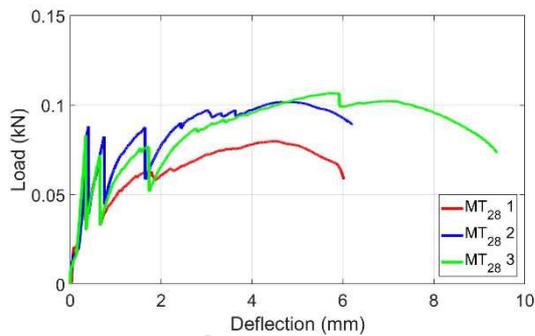
562

563

(a)



(b)



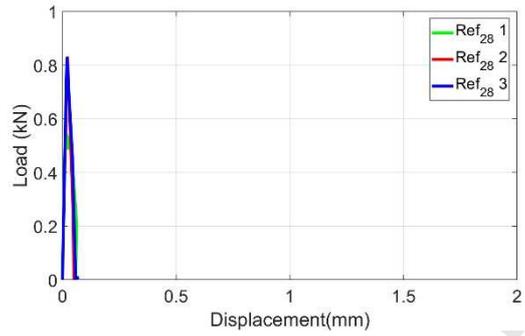
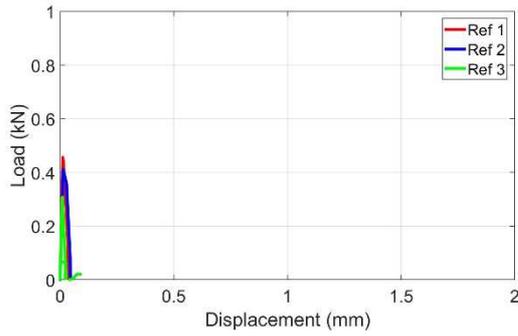
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565

(c)

566 *Figure A.2 Load-deflection curves for 28d specimens tested in 4-point bending. (a) reference (no reinforcement); (b) small*567 *triangles (ST<sub>28</sub>); (c) mixed triangles (MT<sub>28</sub>).*

568 Load-Displacement curves of tension tests are shown in Figure A.3.

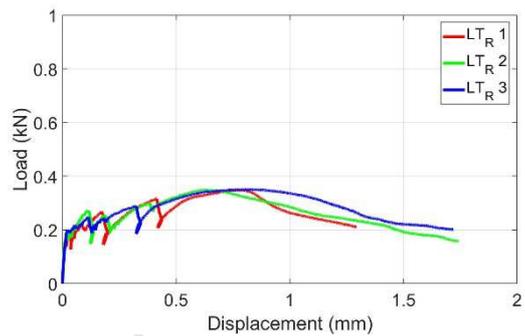
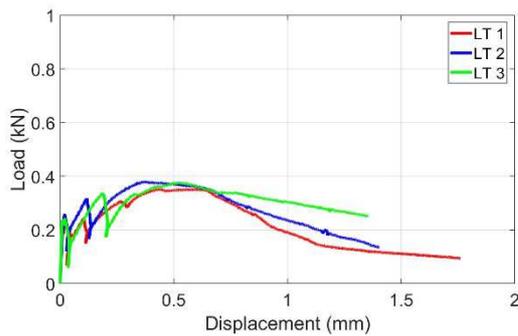


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(a)

(b)

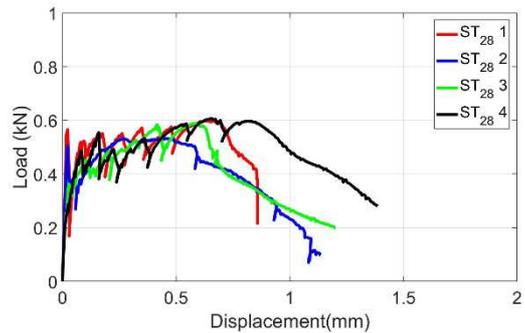
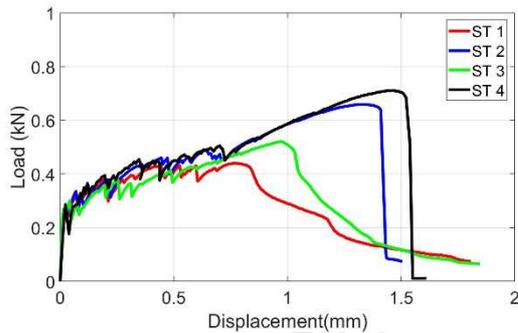


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(c)

(d)



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(e)

(f)

575 Figure A.3 Tensile Load-displacement curves. (a) reference (no reinforcement) at 7d; (b) reference (no reinforcement) at  
 576 28d; (c) large triangles at 7d (LT); (d) large triangles with a rough surface at 7d ( $LT_R$ ); (e) small triangles at 7d (ST); (f) small  
 577 triangles at 28d ( $ST_{28}$ ).

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