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3D PRINTED CONCRETE BEAMS WITH VARIED REINFORCING TECHNIQUES' STRUCTURAL BEHAVIOUR

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Abstract:

3D printing of concrete (DCP) opens up a wide range of new options. By creating more efficient buildings, this technology has the potential to boost construction productivity while also reducing the industry's environmental effect.There has been very little work made into devising reinforcing techniques that are compatible with 3DCP and characterising their structural behaviour, despite major advancements in materials science. As a result, 3DCD does not meet structural integrity standards. Extrusion 3DCP beams reinforced with different forms of reinforcement were tested in nine four-point bending tests in this research. Steel cables (0.1 percent) or aligned end-hook fibres (0.3 and 0.6 percent) were employed as interlayer shear reinforcement. Unbonded post-tensioning and conventional bonded passive reinforcement were considered as options for longitudinal reinforcement. Digital image correlation was used to monitor the fracture patterns and their associated kinematics. As a consequence of concrete crushing during bending, the post-tensioned beams failed in a brittle manner, with deformations confined to a few bending fractures. The brittle failure of the interlayer shear reinforcement in the conventionally bonded longitudinal reinforcement reduced the ultimate load in the beams. As observed crack motions reveal, the interlayer shear reinforcement handled the bulk of the applied stress during the cracking process. Based on these findings, a simple mechanical model is developed to understand the mechanical behaviour and to pre-design the required amount of interlayer shear reinforcement.

1. Introduction

Construction sector, comprising the building industry [1] consumes and emits a significant amount of energy and greenhouse gas emissions. To deal with the challenges of climate change, it must dramatically lessen its negative influence on the environment. Cement and concrete usage, as well as the substantial CO2 emissions from clinker manufacturing, account for a large portion of the construction industry's negative environmental effect. Changes to a variety of elements are required to alter the effect. According to Favier et al. [2], several circumstances and behaviours were highlighted in a recent research [2]. The requirement for structurally more efficient structures that use less material, which must be addressed by structural engineers, is highlighted in the majority of acts taken by materials scientists.

In contrast, traditional procedures for the manufacturing of structurally optimised building parts are very problematic because of the high expense and waste of formwork when generating non-standard forms [3,4].

When it comes to building buildings that are both efficient and cost-effective, emerging technologies such as digital fabrication with concrete (DFC) may be the answer. Concrete extrusion 3D printing (3DCP) [5,6] is the most widely used technology in this field and is also known as contour crafting. Concrete is extruded in layers, one on top of the other, to make an exact replica of an item. Around the globe, scientists and engineers are working to perfect this technology [3,7]. These efforts have resulted in a significant reduction in technical and material restrictions. However, very little effort has been made to yet to design appropriate reinforcement techniques. That's why it's difficult to use 3DCP since it doesn't meet structural integrity criteria.

need little in the way of structure. Load carrying capability resembles that of masonry rather than structural concrete [8,9], hence they cannot replace load-bearing structural concrete parts.

Consequently, 3DCP must be able to handle a wider variety of structural aspects, including more structurally demanding constructions, in order to have a substantial influence on construction sustainability. Concrete buildings with non-standard forms may be built using extrusion concrete manufacturing that is compatible with reinforcing schemes [10]. To meet all structural integrity criteria for load-bearing capability and serviceability, these solutions must supply appropriate reinforcement amounts [11].

Strengthening traditionally cast buildings is accomplished most often by the use of deformed steel reinforcing bars put in the mould before casting. Concrete is cast or sprayed around a preplaced reinforcing cage in Digital Casting Systems [12,13] and Shotcrete 3D Printing [10,14], respectively. Structural concrete standards may be used to design the resultant structures, which offer continuous reinforcement. Because of the high likelihood of a collision between the extruder and the rebar, this method cannot be used in conjunction with 3DCP. 3DCP may be used with conventional reinforcing bars in a variety of ways. It's possible to put concrete on both sides of a reinforcing mesh rather than having a single nozzle for deposition. Classen et al. [17] suggest to extend the reinforcement by welding additional reinforcing bar segments since the height of the reinforcement is restricted in this manner. External [18] or internal [19,20] 3DCP elements employed as lost formwork may also be reinforced after the printing process. After printing a structure with voids, reinforcement and grouting may be added to the voids to further optimise this process. Printing and reinforcing the printed concrete as a structural component is equal to traditionally cast structural concrete in terms of tensile strength. Conventional deformed rein-forcing bars, on the other hand, provide two significant obstacles to 3DCP: Rebar corrosion may be accelerated by increasing porosity at the interface between layers, resulting in a decrease in the structural integrity [21].

Alternatively, prestressing reinforcement, which may be pre-tensioned or post-tensioned, is another common method of long-span structural reinforcement. Only post-tensioning has been used to 3DCP thus far, according to the authors' knowledge. In order to pre-compress the concrete, post-tensioning reinforcement is placed in the voids left by the manufacturing process and then prestressed. The post-tensioned reinforcement may be grouted or left unbonded. Since the tendons can adjust to non-straight voids without excessive curvatures, this strategy is promising for 3DCP. A wider degree of geometric freedom may be gained when employing fibre reinforced concrete (FRC). Fibers, mainly produced from wood, are used in FRC.

Concrete is combined with steel or polyolefins, and then poured into the moulds at the same time.

Fibre-reinforced concrete (FRC) research has been ongoing for decades, but its usage is currently restricted to certain applications such as facades, industrial floors, and tunnel linings. Behind the most part, the reasons for FRC's restricted utilisation stem from two factors. In the design process, there is a great deal of uncertainty due to the fact that the fibres are randomly spread throughout the matrix. For realistic fibre doses, typical FRC exhibits strain-softening behaviour. Failures with damage localization that lack adequate ductility to provide a safe design for the main load transfer are the outcome of this softening. Unless other parts of a structure can compensate for the softening behaviour by resisting greater load, the primary load transfer is not safe. Three-dimensional computer-generated-printing (3DCP) mixtures have been found to increase mechanical performance by aligning fibres in the direction of printing [27–30]. A further layer of perpendicular reinforcement is required to ensure that the fibres may cross over into the next printed layer. Fibres in the concrete mix have a direct impact on the manufacturing process. It is common for 3D printing procedures to depend on pumping material to the extruder. As a result, only short, flexible fibres, which are often more costly and structurally less efficient, may be employed in order to make the material pumpable.

3DCP-specific ways exist in addition to these reinforcing notions that are closely related to conventional methods. The addition of a flexible reinforcement cable, which can be bent to fit any printing route, is one of these methods. It is difficult to anchor this rein-forcement, which has been employed in previous experiments using high-strength smooth steel or carbon strands [31,32], in the direction of printing. Reinforcement bars that are put perpendicular to the printing direction have also been used in other experiments [34–36].

Discontinuity of reinforcement and the length of lap splicing necessary to maintain the continuity of various segments are the key challenges for these techniques.

Only a handful of these reinforcing techniques have been examined at a structurally significant size, even though several have demonstrated promising mechanical performance on a material scale [18,23,37,38]. These structural tests were conducted on complicated geometries utilising a single structure, which should be emphasised. Consequently, the findings cannot be applied to other structures or used to construct mechanical models readily. Because of this, more structural testing is required to better understand reinforced 3DCP parts' structural performance.

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2. The importance of the research

To have a long-term influence on the building sector, 3DCP will need reinforcement measures. A ductile reaction is required; (ii) the geometric flexibility of 3DPC is not restricted; (iii) the cost is minimal; (v), the environmental effect is low; and (vi) an automated production method is possible. There are currently no or just partly effective reinforcement mechanisms for 3DCP. Furthermore, nothing is known regarding their structural behaviour. This research examines the behaviour of a 3DCP component under structural loads and the efficiency with which a 3DCP structure may be reinforced. Interlayer shear reinforcement is added during the printing process (aligned in the printing direction) and longitudinal continuous reinforcement is installed post-printing in printed voids (perpendicular to the printed layers). This reinforcement idea is shown in Fig. 1. Longitudinal reinforcement is evaluated using both unbonded post-tensioning bars and bonded conventional reinforcement. High-strength steel cable or aligned fibre reinforcement is inserted between the layers of concrete for interlayer shear reinforcement. Interlayer shear reinforcement behaviour is also examined.

With nine four-point bending tests on extrusion 3DCP beams with basic geometry, these reinforcing techniques are compared to standard concrete constructions and their structural performance is evaluated in a more thorough manner than complicated geometries. Using digital image correlation, the fracture patterns and their related kinematics are explained and utilised to predict the shear reinforcement's load. Following analysis, a basic mechanical model is constructed to better understand mechanical behaviour and provide more straightforward design suggestions.

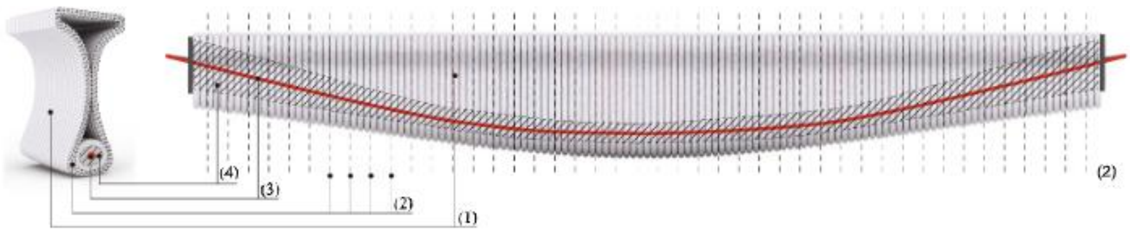

Fig. 1. Concept of the reinforcement strategy illustrated for a beam of complex geometry. (1) 3D concrete printing filament; (2) interlayer shear reinforcement

3DCP Reinforcement Methods Proposed

3.1. Long-term support

The principal loads of a structure are carried by the longitudinal reinforcement. As a result, techniques for reinforcing conventionally cast concrete buildings that have been successful are selected.

The major reinforcement should be continuous, have a ductile response, and justify a structural behaviour that can be validated according to structural design code standards, often based on the lower bound theorem of plasticity theory.. Reinforcement may be added to voids to provide continuity in 3DCP, whether it be passive reinforcing bars, active reinforcing bars, or tendons.

Straight and stiff bars may be used for basic geometry. Non-straight empty tendons may be utilised for more complicated geometries, but be aware that curved prestressing tendons create deviation forces that need to be taken into account in the design. Note: Alternatively, the space may be filled using grout to provide a strong link between the reinforcement and the concrete. Only straight longitudinal reinforcement is examined in this research for ease of reference. Unbonded post-tensioning is used to prepare one set of beams, while bonded passive reinforcing bars are used to prepare the other set. The structural behaviour of these techniques has previously been used by other writers (see Section 1), but the results were not extensively documented.

3.2. Shear reinforcement in the interlayer

Compared to longitudinal reinforcement, shear reinforcement has a lower structural demand. For example, design rules often specify lower minimum reinforcement ratios for stirrups compared to other parts of the structure.loadings. Strain hardening of the entire member may be accomplished even with strain softening shear reinforcement [26], provided that the longitudinal reinforcement is capable of withstanding an extra load. When shear reinforcement is introduced during concrete printing, the printed pieces become structurally active rather than merely lost formworks. In order to produce complex structures, this reinforcement must I allow for great geometric flexibility, and (ii) be readily added to the printing route, either in the matrix itself (i.e. printing of FRC) or added independently during printing to guarantee an efficient overall process. Reinforcement applied during printing is not addressed in this work. This means that the reinforcing was always done by hand, as detailed in Section 4.3.2 above.... Using a steel cable as an interlayer shear reinforcement has been proved to be a feasible technique for automatically putting continuous reinforcement [31]. [31] Another approach is being investigated because of the difficulties in anchoring high strength smooth wires [33]. Instead of using a wire to connect the layers of concrete, this approach utilises steel fibres. Aligned interlayer fibre reinforcement is referred to as this approach and is explained in the next paragraph.

For example, Ahmed et al. investigated the use of aligned interlayer fibre reinforcement to benefit from the geometric freedom provided by short discon- tinuous fibres and to overcome several processing challenges that arise when the fibres are added into 3DCP mixes (i.e., rheological changes, the inability to pump long fibres...). Since the fibres may be put independently of the concrete printing, the authors devised a reinforcing strategy (see Fig. 2). Every time a new concrete layer is put down, a robotic fibre placer adds fibres to the current layer. When the nozzle returns to print the next layer, the fibres are coated in concrete once again, and the process repeats. Rather of being restricted by the processing limitations of the concrete matrix, this method lets you print objects with greater fibre lengths simply because of their general geometrical design. An additional benefit of this method is that it may align fibres under tensile stresses and grade fibre dosage in accordance with structural requirements.

As part of the alignment of interlayer fibre rein-forcement, bending tests were used to determine the mechanical performance of the fibres at doses of 0.7 and 1.4 percent [42]. When the fibres are aligned and/or graded in the right places, they are more effective. The maximum load was, however, restricted by a severe and rapid softening caused by the delamination of layers at high fibre doses.

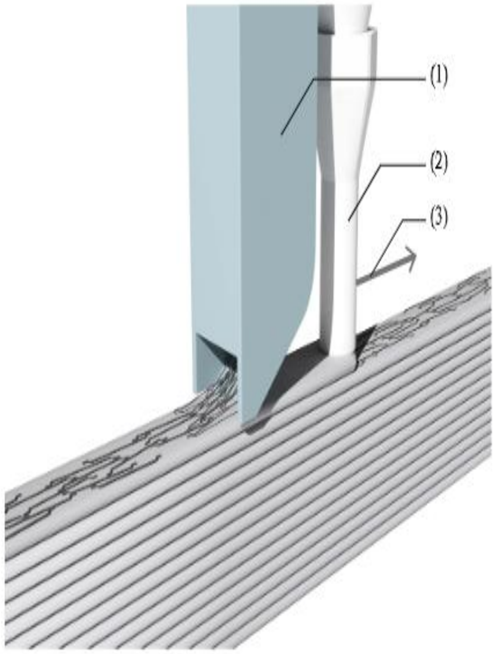

Fig. 2. Schematic sketch of the interlayer fibre reinforcement concept for3DCP: (1) fibre placer, (2) extruder nozzle, (3) printing direction.

as a transverse (i.e., shear) reinforcement in conjunction with an alternate longitudinal reinforcement, which is addressed in the experimental campaign detailed in the next chapter despite the challenge of obtaining strain hardening and adequate deformation capacity

Fourth, a research project

Testing and specimens 4.1

Nine four-point bending tests on beam specimens with and without interlayer reinforcement were undertaken as part of the experimental programme. First Series 1 was comprised of four beams with unbonded longitudinal post-tensioning reinforcement. The remaining five beams have longitudinal reinforcement that was passively linked (Series 2). As can be seen in Figures 3 and 4, the beam shape and test setup can be seen in Figures 3 and 4, while Table 1 provides a summary of all samples. All specimens were produced vertically and turned by 90 degrees for testing as horizontal beams.

Series 1's four beams have a nominal cross-sectional width of 150 millimetres and a nominal height of 300 millimetres. A single filament with a printing width of roughly 45 mm and a layer height of 5 mm was used to create the cross-section. The printing width was set at the same value as the web width for this run. Table 1 provides the precise bweb value for the web width. Series 1's printing process generated four half beams every printing session. Of these, two were reinforced exclusively in their webs with aligned interlayer fibres, at a dose of roughly 0.3 percent (B- 1xx-F03), while the other two were made without reinforcement (see specific values of web in Table 1). (B-1xx-NR). Reinforcement was applied manually to all beams between each layer. Despite the fact that the fibres are concentrated in the interlayers, the reported fibre doses are based on the average dosage per volume of concrete.

Once the interlayer reinforcement was printed, the two ends of the beam segments were cut to provide a level and smooth surface for joining the halves and attaching the steel anchoring plates. A 1.5-meter-long beam was created by glueing together two half beams. So that the printed rough surface could be properly loaded, mortar beds were poured where the load and the supports would be applied.

Additionally, gypsum was used to make a flat surface and painted white on one side of the beam so that the digital picture could be speckled.

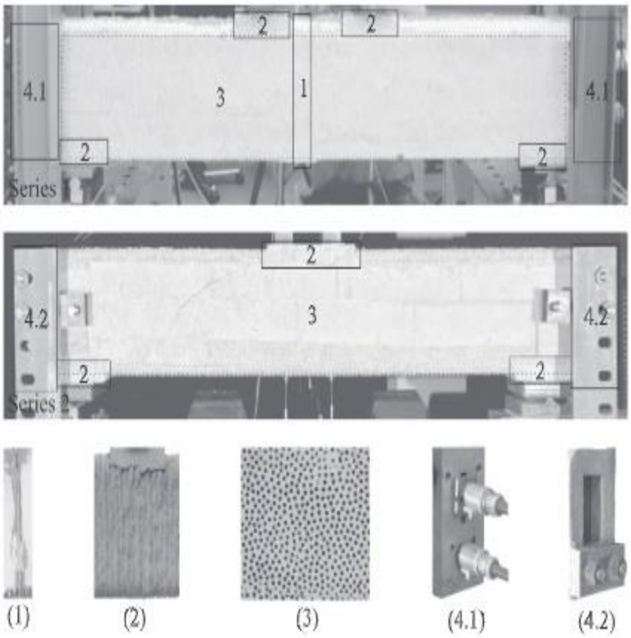

Fig. 3. Test preparation steps for Series 1 and 2: (1) Glueing of two segments(Series 1 and B-231-F06); (2) Mortar beds; (3) Gypsum surface painted whiteand speckled; (4.1) Post-tensioning reinforcement with anchorage plate andforce measurement (Series 1); (4.2) Passive reinforcement with anchorage plate (Series 2).

7. Conclusions

Due to its automation possibilities, digital fabrication with concrete(DFC) offers the potential to build complex structures with similar effortas standard geometries, but with enhanced structural efficiency andreduced material consumption. However, reinforcing approaches forDFC are not yet developed to ensure compliance with structural integrityrequirements, which hinders the implementation of the technologies. Astudy of requirements for reinforcing for 3D printed concrete (3DCP)indicated that:

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