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Investigation of Mechanical Properties of Structures Created with Use of Automatically Reinforced 3D Concrete Printing – Preliminary Study

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ABSTRACT

The 3D concrete printing (3DCP) technology is a rapidly developing and promising technique for creating concrete structures. One of the main challenges of the 3DCP technology is the method of reinforcement, which should be integrated with the automated printing process, while maintaining the best mechanical properties important for the strength of the structure. The main reason to undertake the subject is low degree of automation in construction industry, which results in high cost of human labour, as well as high rate of accidents in process. The article proposes a technology for automatic reinforcement of concrete structures with glass fibres and epoxy resin. Maximum bending force tests of the beams reinforced with the proposed method were carried out and compared with the beams reinforced with commonly used methods. Although not being an article focused on DIC analysis, several images were presented to compare the behaviour of non-reinforced beam with automatically reinforced one and to show cracking propagation of a chosen automatically reinforced beam. The proposed method of reinforcement in the 3DCP process enables full automation and constructions with high bending strength, simultaneously reducing the level of risk involved in conventional construction industry.

Keywords: 3D concrete printing, concrete reinforcement, automatic reinforcement, continuous fibre reinforcement.

INTRODUCTION

Advances in computational power and programs allow for changing the way of designing, constructing and managing the built environment today. The use of computational intelligence ranges from urban, via architectural, up to the industrial design scale. Several computational methods have been developed for generative design of urban forms [1, 2, 3], as well as the evaluation of the quality of existing urban compositions [4, 5]. Relatively new studies on crowd simulations have also been used for safety [6] and comfort [7] in urban and architectural environments as well as for the floor-plan optimization [8]. The modern means of modular systems and automation have been proposed for several areas of urban and architectural environment, in particular for improvement of the accessibility [9] and pedestrian safety [10].

Even relatively exotic phenomena which emerged strictly from computer science such as cellular automata have been proposed for several areas related to the built environment, e.g. as a support for the architectural design process [11, 12], as a form generation method in high density residential buildings [13], and even for aesthetic and shading applications on building facades [14], and for the prototypes see [15]. For a review of Artificial intelligence applied to conceptual design in architecture see [16]

Despite all these computational and technological advancements, many researchers have noticed that the potential of automation, which can contribute to a faster and more economical way of production, has not been exploited as much in the construction sector as in other industrial sectors [17]. The potential of automation, which can contribute to a faster and cheaper way of production, has not been exploited as much in the construction sector as in other industrial sectors. Traditional construction techniques have many disadvantages, ranging from high injury and accident rates [18] to high labour dependency, low productivity, and high costs [19]. So far, technological progress has concerned the replacement of the traditional technique of mixing and pouring concrete on the construction site with precast or prefabricated construction. Further automation of the process can reduce the number of accidents on the construction site and have a positive impact on costs and construction time [20]. The 3D concrete printing technology is rapidly gaining popularity among architects and construction engineers as a faster and cheaper method of building, having potential advantages such as reduced material use, decreased labour, increased construction speed, and production flexibility, in addition to allowing especially complex and customised geometries [21, 22]. However, it is also important to keep in mind the disadvantages and limitations of this technology, especially the mechanical properties of the printed structures.

The 3D concrete printing technology (3DCP), also referred to as additive manufacturing (AM) of cementitious materials, is a technique primarily using layer-by-layer extrusion for material deposition to form 3D objects directly from digital models [23, 24]. A concrete structure produced in this way has numerous disadvantages, mainly related to the low strength of the material. In traditional construction, this problem is solved by using prefabricated reinforcing bar structures. Concrete reinforcement is also intended to protect the material from brittle fracture failure, to provide sufficiently ductile behaviour to allow stress redistribution, as well as to limit deformation and crack width. Due to the nature of the layer-by-layer printing process, the strength and quality of the bond between the extruded layers, which can be induced by gravity or by chemical bonding, is also important. In 3D-printed constructions, the quality of interfaces between layers and bonding method can be the major weakness point of this technique, since they affect the durability and strength of the bond [25, 25].

In order to achieve better structural performance and structural reliability, concrete structures generally require the addition of reinforcement. Reinforcement can be achieved in various ways, depending on the design requirements and structure characteristics. One of the most popular methods to reinforce a structure in 3DCP technique is to place prefabricated reinforcing steel rebar during printing, by embedding them in the concrete during the printing process [27–29]. Bars can be placed at specific locations to reinforce the structure at critical points, such as where heavy loads or pressures are present. Another method of reinforcing the structure using precast elements is the use of reinforcing wires or reinforcing meshes, which are placed inside the concrete structure after the printing process is completed [30–32]. Integration of reinforcement in 3D-printed concrete components is crucial to ensure good bond with the surrounding material and stress transfer with the least risk of concrete cracking. The reinforcement should be arranged according to the principal stress trajectories [33]. Steel reinforcements form sufficiently strong bonds with the concrete to transfer the force of the bars to the concrete, and they also have a similar coefficient of thermal expansion. The main disadvantage of steel reinforcement is the risk of corrosion, which is a frequent cause of structural degradation.

Composite reinforcements, such as fibre-reinforced polymers (FRPs) [34], which are not susceptible to corrosion and perfectly withstand adverse environmental conditions constitute an alternative. In addition, FRPs have high tensile strength and electromagnetic inertness [35]. Composite reinforcement consists of continuous fibres embedded in a polymer resin. The main role of the fibres is to ensure the appropriate strength and rigidity of the composite, while the resin is responsible for connecting the fibres with the appropriate distance between them, protecting their surface against damage and transferring stresses to them [36]. The durability of FRP rebars is more difficult to determine than that of steel, because the degradation of the material can depend on both the resin and fibres as well as their behaviour at the interface [37, 38]. There are many commercial solutions available on the market, and each will have a different durability.

Among the conventional methods of 3D concrete printing reinforcement prestressed (active) cables [39] and wire mesh reinforcement [32, 40] should be mentioned. In order to change the mechanical properties and strengthen the structure of the 3DCP print, the method seemingly the easiest to integrate is the dispersed-fibre reinforcement concrete, where materials such as glass fibre, synthetic fibre, natural fibre or steel fibre [41] are added to the concrete [42, 43]. In fibre-reinforced concrete, when cracks occur under loading conditions, the fibres perpendicular to the crack planes tend to hold the crack and prevent crack propagation. In addition, they can reduce the number of plastic shrinkage cracks during hardening and hardening of concrete [44].

Methods are also being developed that aim to fully automate the 3D concrete printing process in which reinforcements are created. A 3D printing process was implemented using gas-metal arc welding [45]. The aim was to integrate the steel reinforcement and cement printing process. Another proposed method is to add reinforcement during the Contour Crafting printing process [46]. In this method, the reinforcement can follow the geometry of the structure, owing to a robotic feeding system of steel mesh reinforcement that is embedded in each layer of concrete. The reinforcement may be continuous or discontinuous, as required.

The knowledge and possibilities of 3DCP technology are developing rapidly, but still the weakest point of this technology is the effective incorporation of reinforcement into the printing process. The most commonly used are traditional reinforcements of concrete structures with steel or composite, which cope well with tensile stresses, but do not solve the problem of interlayer reinforcement, which is crucial in the implementation of construction projects. During bending, stresses in the material also have a direction consistent with the course of the layers; therefore, it is the transverse direction that is the most critical. Currently, there are many methods and technologies for reinforcing the material in the 3DCP technology, but none of them are sufficiently effective and efficient. In order for the construction automation process to go further, it is necessary to develop reinforcements in the 3DCP technology that will effectively strengthen the structure. The article proposed an approach to automated reinforcement of concrete structures using glass fibres and epoxy resin, and presented the results of destructive strength tests of structures obtained using this technology.

METHODS

The method developed and tested in this work is an automatic composite reinforcement method where the reinforcement is placed during the 3DCP process. It differs significantly from the methods using prefabricated reinforcement due to the full automation of the process. The aim of the article was to compare the mechanical properties of beams reinforced with commonly used methods and the method developed by the authors. The research presented in the article was carried out in connection with conducting research work on the reinforcement of concrete structures made using 3D Concrete Printing technology. Samples of all types were printed using a 3D concrete printer. The printing and reinforcement process involved five stages. The first was to print the bases of all samples, with a thickness 25 mm of one layer, and a width of three tracks, a total of 150 mm. After printing the bases, the printing process was stopped and the appropriate type of reinforcement was applied, as shown in Figures 1 and 2. Then, additional 4 layers of concrete were printed and the samples were reinforced again. The last stage was printing the last, 6th layer of concrete. Ultimately, each of the samples had dimensions of 150×150 mm. Each of the test beams was obtained by applying 6 layers of concrete with a thickness of 25 mm and applying reinforcement between layers 1–2 and 5–6. The diagram of beam is shown in Figure 3. The automatic reinforcement of concrete in the 3DCP technique developed by the authors

Figure 1. Printing the second layer of concrete (with a trapezoidal nozzle) of an automatically reinforced beam (sample no. 42RT)

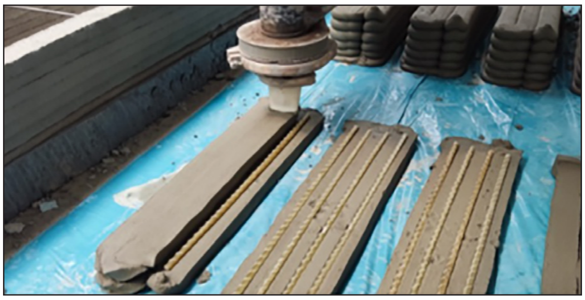

Figure 2. Printing the second layer of concrete beam (with a trapezoidal nozzle) in a conventional composite reinforced beam (sample no. 11KT)

was obtained as a result of continuous additive composite reinforcement. Automated reinforcement was performed using a CNC machine. The glass fibres were pulled through a pan with epoxy resin and then applied according to the developed G-code in specific trajectories during the 3DCP concrete printing process.

The maximum bending force of four types of printed beams was tested:
- concrete with conventional prefabricated steel reinforcement,
- concrete with conventional prefabricated fibreglass in an epoxy resin matrix composite reinforcement manufactured by Bascoglass,
- concrete without reinforcement,
- concrete with reinforcement made according to the technology proposed by the authors.

The maximum bending force test was carried on 6 pieces of concrete beams of each type. The test was carried out on a CONTROLS class 1 testing machine according to ISO 75000-1 with a force of 3000 kN. The same procedure of preparation and care was maintained for all samples. The temperature during the test was 20 ± 0.5 °C. The load increase rate was 0.7 MPa/s. For comparison, 3 out of 6 samples of a given type were made using a round nozzle, the remaining 3 using a trapezoidal nozzle applying concrete. The automatically reinforced beam destroyed in the bending process is shown in Figure 4.

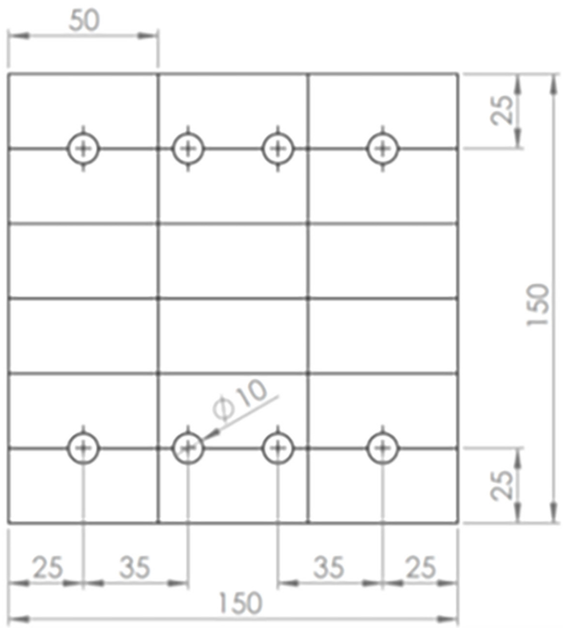

Figure 3. The diagram of reinforced beam

During bending tests, the DIC technique was employed in order to track propagation of cracking (Fig. 5). Dantec Dynamics DIC system with two cameras and Istra 4D software were used.

RESULTS AND DISCUSSION

Bending test results are displayed in Tables 1–4, showing the results of the maximum bending force for each of the samples (Fig. 6). The differences between the types of nozzles used are so small in the context of the differences between the different types of reinforcement that they can be ignored. The comparison between the measured properties is shown in Figure 7.

On the basis of the conducted research, it can be seen that the proposed solution for automatic composite reinforcement during the 3DCP process has very favourable properties compared to commonly used solutions. Maximum transmitted force is averagely higher for the beam reinforced automatically than for the beam reinforced with commercial composite or without reinforcement.

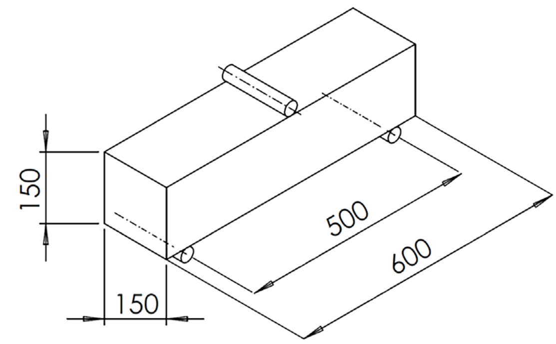

Figure 4. Diagram showing the outer dimensions of beams and support span

Figure 5. The beam without reinforcement (sample no. 23-T) destroyed in the bending process

Table 1. Maximum bending force test of beams with composite reinforcement

Sample no.	Nozzle type	Max force [kN]
11KO	Round	30.33
12KO	Round	40.79
13KO	Round	32.12
11KT	Trapezoidal	43.93
12KT	Trapezoidal	33.11
13KT	Trapezoidal	35.93

Table 2. Maximum bending force test of beams without reinforcement

Sample no.	Nozzle type	Max force [kN]
21-O	Round	9.76
22-O	Round	14.23
23-O	Round	12.29
21-T	Trapezoidal	8.82
22-T	Trapezoidal	13.19
23-T	Trapezoidal	9.78

Table 3. Maximum bending force test of beams with steel reinforcement

Sample no.	Nozzle type	Max force [kN]
31SO	Round	44.48
32SO	Round	57.29
33SO	Round	55.94
31ST	Trapezoidal	45.35
32ST	Trapezoidal	43.13
33ST	Trapezoidal	34.52

Table 4. Maximum bending force test of beams with automatic reinforcement

Sample no.	Nozzle type	Max force [kN]
41RO	Round	58.40
42RO	Round	34.22
43RO	Round	25.91
41RT	Trapezoidal	44.65
42RT	Trapezoidal	39.67
43RT	Trapezoidal	59.05

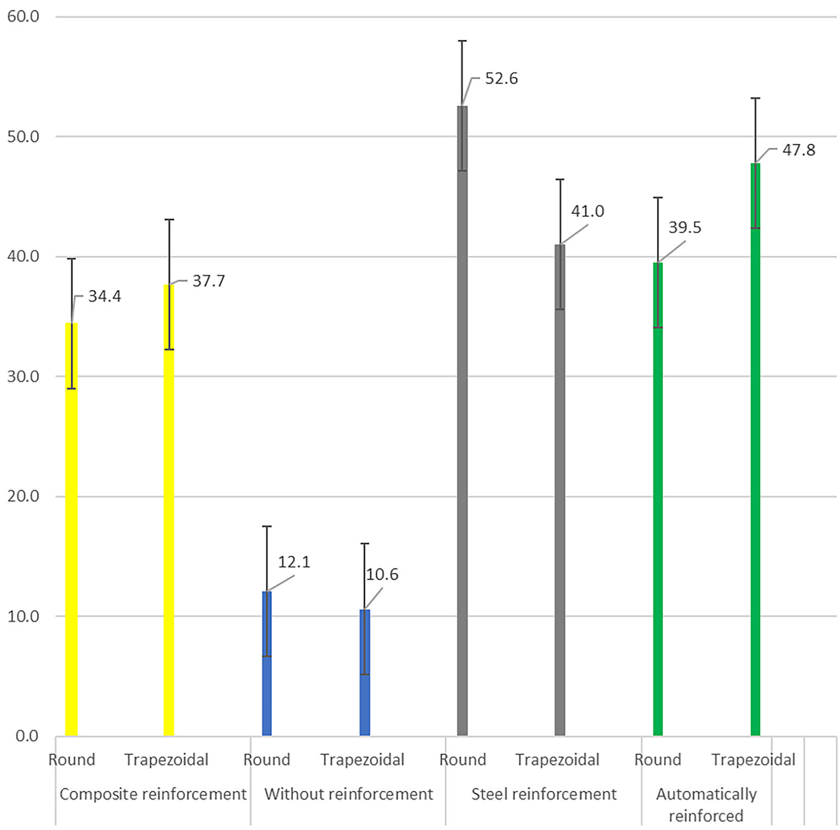

Figure 6. The diagram comparing the maximum bending force [kN] of beams with different types of reinforcement, for different types of nozzles, with standard deviation

A beam reinforced with the authors' technology carries, on average, more than 120% of the failure load of a beam reinforced with prefabricated composite bars. The average value of the destructive force for an automatically reinforced beam is less than 10% lower than for a steel-reinforced beam.

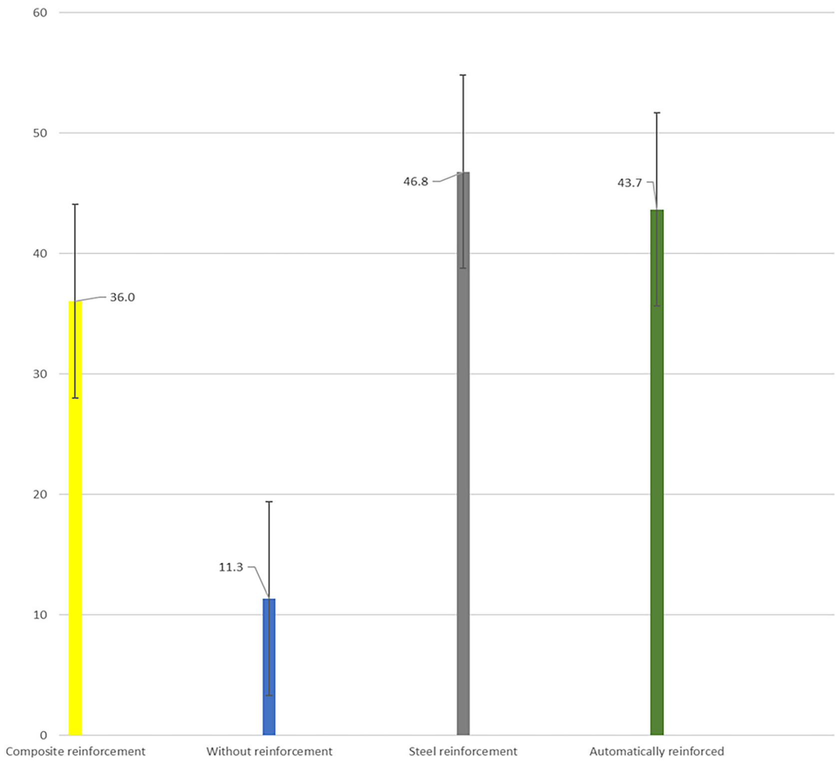

Figure 7. The diagram comparing the maximum force load [kN] of beams with different types of reinforcement without nozzle differentiation, with standard deviation

The substantial variability in the experimental results can be due to many factors influencing the sample production process. The most straightforward and likely explanation for this phenomenon is the inherent imperfections in the still-evolving fabrication technology. Key imperfections include variables such as the quantity of resin used to moisten the fibres, the difference in fibre shape owing to variations in individual fibre lengths drawn during the process, inconsistencies in pause durations, and the evolving properties

Figure 8. Automatically reinforced beam (sample no. 41RT) after three-point bending test

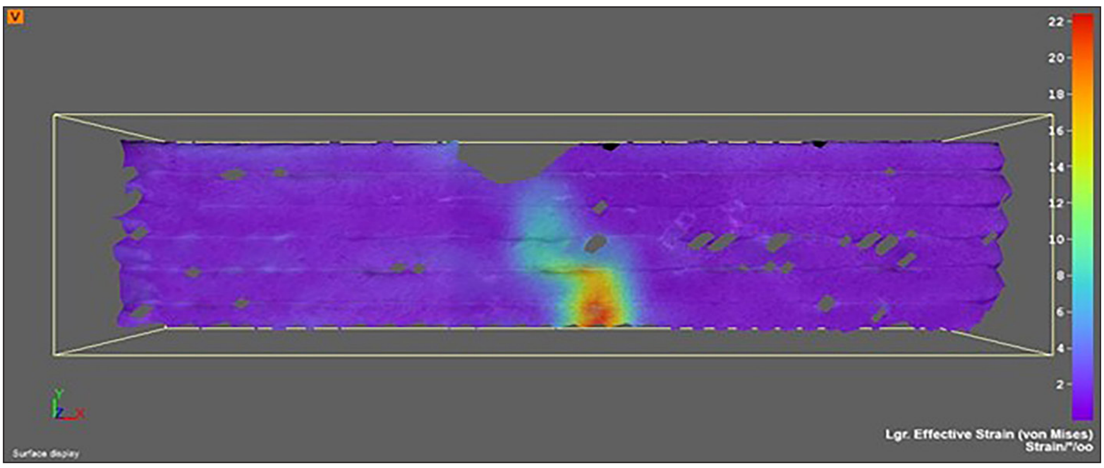

Figure 9. Image of non-reinforced sample (23-T) von Mises strain

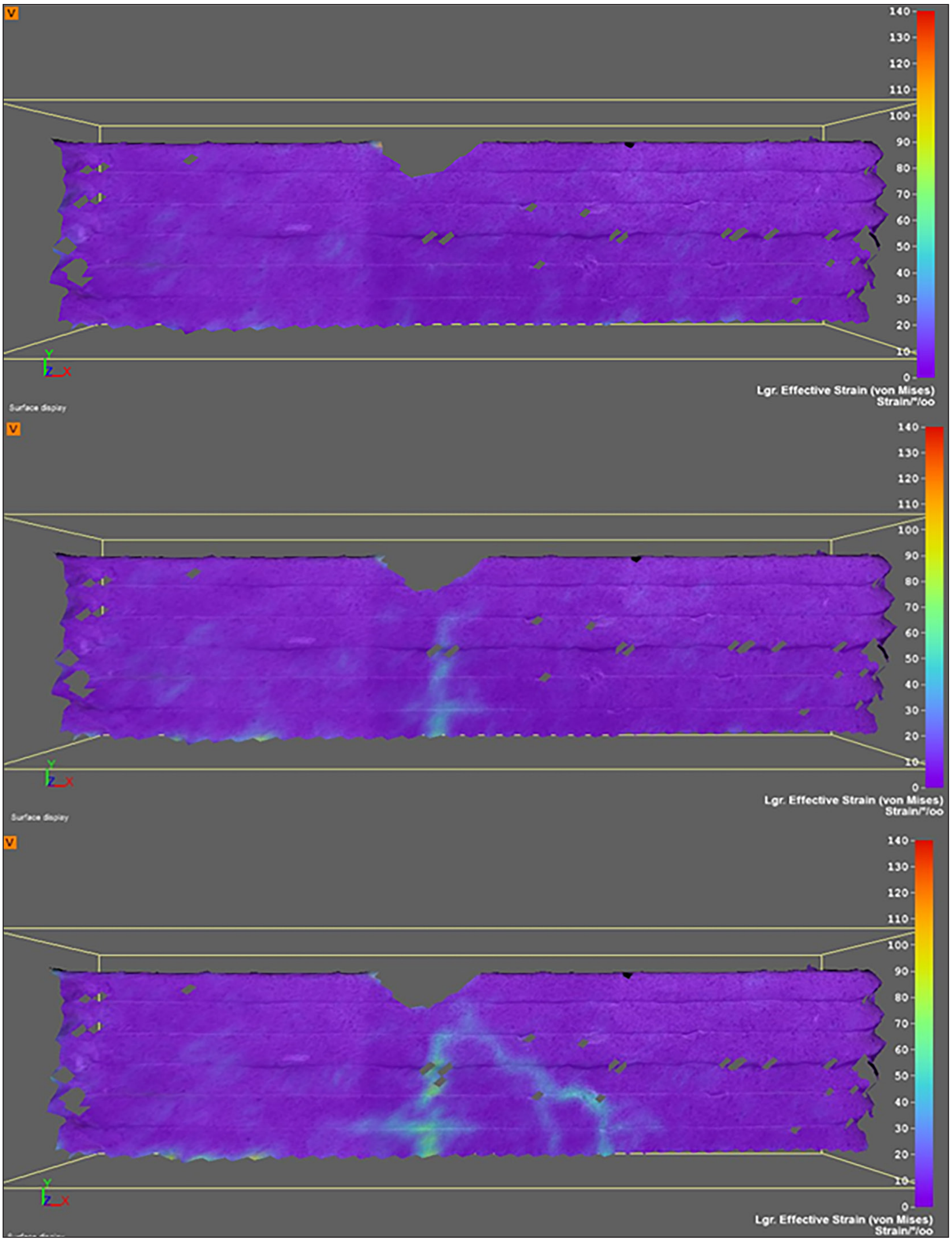

Figure 10. Istra 4D images of automatically reinforced beam (sample no. 41RT) in steps 20, 50, 65 –corresponding forces 2.6, 16.5, 22.5 [kN]

of the printed concrete. Although the concrete is composed of identical ingredients in consistent proportions, its characteristics fluctuate over time and are sensitive to temperature changes, which tend to increase due to exothermic chemical reactions occurring within the concrete mix. Additionally, the dispersion is influenced by the anisotropic nature of the printed concrete, coupled with the adhesive forces between the printed layers. These properties are significantly dependent on the characteristics of the concrete and are currently the focus of ongoing research conducted by the authors. As this research is in its preliminary stages, the direct consideration of these factors in the current analysis is not feasible.

While digital image correlation (DIC) analysis is not the primary focus of this study, the methodology provides insightful visualisations of crack

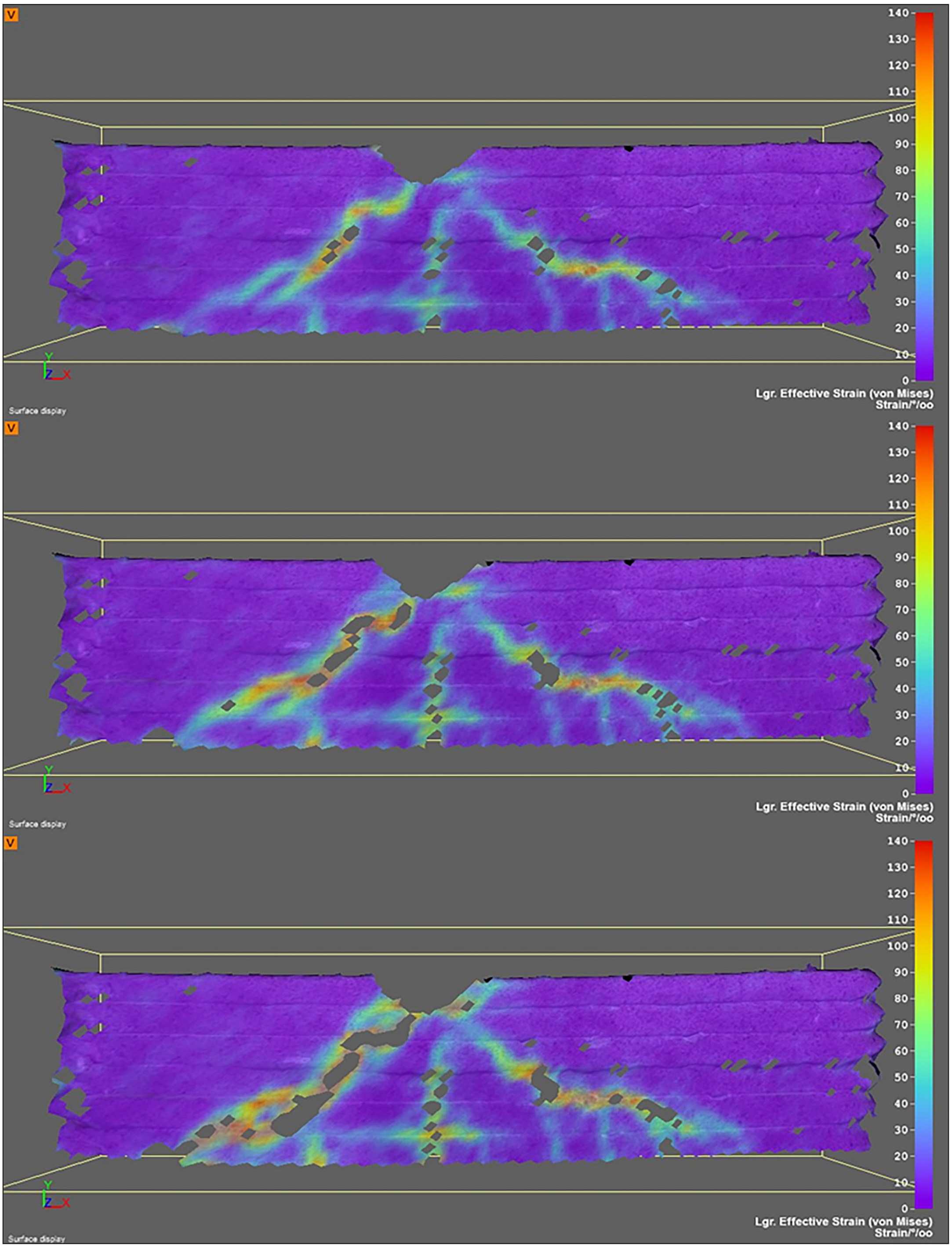

Figure 11. Istra 4D images of automatically reinforced beam (sample no. 41RT) in steps 85, 100, 111 – corresponding forces: 32.2, 40.9, 43.1 [kN]

propagation in concrete structures. Figure 9 illustrates the von Mises strain distribution in a non-reinforced concrete beam, revealing peak strain concentrations at the central lower region, a characteristic response under three-point bending stresses and the absence of reinforcing elements. Figures 10 and 11 sequentially capture load conditions for an automatically reinforced beam, clearly indicating the direction of crack propagation trajectory. The crack in its course has the tendencies to navigate through inter-layer regions within the concrete, frequently altering its path, when encountering these interfaces. Bottom part of Figure 11, corresponding to step 111, presents the moment of the major crack noise emission. Despite a temporary reduction of applied force from 43.1 kN, it eventually increased to 44.7 kN, when a large part of the beam detached and the experiment was completed.

On this basis, it can be assumed that the proposed method of reinforcement has a very large potential, because it not only enables full automation of the process, but also allows achieving structures with satisfying mechanical properties, comparable to commonly used solutions. The developed method of reinforcement achieves high values of destructive forces. Owing to the resin, the tensile force is most probably transferred more evenly through the concrete-fibre joints in the beam and eliminates the need for braiding or ribs, which serve to better anchor the prefabricated beams in the concrete. A risk and potential disadvantage can be the non-cross-linked resin, which during the printing process can result in slippage of the concrete when applying successive layers. For this reason, it is necessary to avoid starting next print layers in the areas moistened with resin.

CONCLUSIONS

This work presents an original method of automated reinforcement of concrete produced in the 3D concrete printing process. A technique of additive reinforcement of composite fibres in an epoxy resin matrix has been developed, which allows for printing concrete structures in a fully automated reinforcement process. Bending tests were carried out and in comparison with commonly used methods of reinforcement, the method proposed by the authors is very favourable in terms of maximum bending forces. The developed method of reinforcement allows for further development of 3D printing with concrete and expanding the range of products that can be obtained by using this technology.

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