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EXPERIMENTAL TESTING OF 3D PRINTED CONCRETE TRUSS GIRDER

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In the last few decades, the technology of 3D concrete printing (3DCP) has had a significant development. This technology has a great potential to improve efficiency in the construction industry. It can provide safer site working conditions, material savings, a reduction of construction time, and a high versatility of architectural and structural design. However, this new technology is still not fully investigated. The wider application is limited by the lack of standards and guidelines for design and production. The literature review showed that, there are only a few studies investigating structural behaviour of 3DCP structures and elements. Beams and walls with and without addition of fibers, reinforcement or cables under ultimate loads were tested. The incorporation of reinforcement in the printing process, connections between printed pieces and long-term behaviour of 3DCP elements under sustained load are opened questions. The topic of this research was an experimental testing of 3DCP truss girder. Printing of truss girder was done using a commercial, ready-to-use premix Sikacrete® 751 3D. In order to print, the printer head was moved in the Z direction to alternately place two desired path layers. A truss girder with dimensions of 87x29x12 cm, without reinforcement, was subjected to a four-point bending test up to failure. During this testing strains in two diagonals, deflection of the two bottom joints, and ultimate force were measured. Ultimate force was 30 kN and the brittle failure of tensioned bottom chord occurred. The force in tensioned diagonal was 13.45 kN and in the compressed one 36.77 kN. Additionally, three samples obtained from the top and bottom chords were tested on axial tension. The tension capacity of samples was 25.12 kN.

Keywords: 3D printed concrete, experimental testing, truss girders, 4-point bending test

1 INTRODUCTION

The 3D concrete printing (3DCP) is a new technology that has been developed in the last few decades. From the laboratory technology that was used for small prototypes and materials like polymers, steel, clay, it has thrive to the technology that can be used for printing real concrete elements and structures [1], [2]. Also, emerging digital fabrication (application of digital modelling and technologies for custom material objects production) enables the possibility of 3DCP mass application [3]. 3DCP is based on the additive manufacturing, meaning that the material is precisely dispensed in layers along the desired path [4]. There are few methods for concrete printing: Contour crafting (CC); Fused Deposition Modelling (FDM) - shape of the object is generated by the G-code and material is extruded in desired path; Shotcrete 3D Printing (SC3DP) - concrete is sprayed by the robotic arm; Ink printing Method - the binder is sprayed onto the material for printing [5].

3D printing technology benefits can improve the construction industry. When comparing the traditional type of construction and 3DCP, overall cost and labour could be reduced by implementing 3DCP, and work safety and amount of produced waste could be lower [6], [7]. Also, 3DCP is a technology that can benefit the sustainability aspect of the construction process, by reducing the amount of global CO2 emissions [6], [8]. Another advantage of the 3DCP application is the possibility to be applied for the fast construction of modular hospitals and houses, which would be an efficient solution for temporary accommodation after natural disasters such as floods or earthquakes. Possibilities for producing various shapes and objects (freeform constructions) are only limited by the printer capacity and creativity of the constructor. Till today object like tiny homes, 2-story houses, sheltering structures, short span beams, pedestrian bridges or segmental bridges were built. Some of those modern objects are shown on Figure 1.

(a)

(b)

Fig. 1. Examples of 3DCP application: (a) World`s longest 3DCP Bridge in Shanghai [9] and (b) Tiny house in Holstebro-Denmark by COBOD [10]

Nevertheless, the 3DCP is still facing various challenges, e.g. difficulty of adding reinforcement into concrete during the printing process [11]. Considering the fact that concretes tensile strength is relatively low, unsolved problem of reinforcement integration hinders the fabrication of elements and constructions. Besides this, the greater application of 3DCP is slowed down by the following obstacles: requirement for skilled labour, higher initial costs, necessity for higher control of material quality, connection between individual segments, and most important, lack of standards [12–16]. Behaviour of elements or structures subjected to the ultimate and serviceability loads is not fully investigated.

2 LITERATURE REVIEW

There are no adequate codes and standard for testing 3DCP elements and constructions, neither for fresh, nor hardened properties of concrete mixtures that are used for printing. In previously published studies, researchers concluded that fresh concrete mixture should satisfy the criteria of pumpability, extrudability and buildability [3]. Also, they concluded that material compressive and tensile strength tests should be performed in order to design the printed element [3]. In relevant literature, some examples of experimental testing of 3DCP elements can be found. Those experiments can be divided into few groups depending on the element type, tests that were performed and type of reinforcement. Table 1 shows the overview of performed tests. Type of elements and tests that were performed, and the type of fibers, reinforcement or cables that were used are shown.

All tests that were performed can be characterized as load/displacement tests. The shape and the dimension of elements were obtained by trial-and-error method, or by using topology optimization. The idea of all researches was to achieve the shape of elements that will have the lowest material consumption. The cross section of beams and walls had different hollow structures. Numerical studies were also performed in order to design elements and calculate the necessary amount of reinforcement or tendon cables. Most of the mixtures were made with micro fibers. It can be concluded that it is possible to produce all kind of elements shapes, but the tensile strain in concrete cannot be avoided. It is necessary to add reinforcement and/or cables for post tensioning. The reinforcement was still manually placed between the layers, and placing of vertical reinforcement was not developed. Cables for post tensing were added after few days/weeks after printing the elements, and the process of adding was similar to the traditionally casted concrete elements. Furthermore, the segmented beams had the additional work on connecting the segments with injecting the connection with some kind of mortar.

The researches follow the path that includes the following steps: 1) preparation and testing of trial samples with or without reinforcement; 2) numerical modeling of tested sample in order to determine the correlation between the tests and numerical study; 3) based on conclusions between test and numerical model, new element is designed, made and tested.

The aim of this article was to analyse the current state-of-the-art in the field of experimental testing of concrete elements and structures made by using 3DCP. Also, own experimental results from the first step of production the new 3DCP element were shown. The truss girder without reinforcement and fibers was made and tested in a 4-point bending test. This type of girder was chosen in order to optimize the concrete consumption. Nonsymmetrical filing and shape of the truss girder was adopted to provide fracture pattern in the tensile chord with maximum strains according to simplified numerical calculation. Testing was performed in order to obtain the results that can enable the production of a real scale element. In the following section the overview of relevant literature is presented

Table 1. Experimental testing of 3DCP elements

Ref.	Type of element	Number of samples	Dimension of elements [cm]	Performed test	Type of fibers	Reinforcement	Cables
[17]	Beam (girder)	1	30x12x10	3-point bending	/	/	/
	Beam (girder)	1			Glass	/	/
	Beam (segmented)	1	250 (span)	4-point bending	/	/	Post tensioning
[18]	Cube	12	15x15x15	Axial compression	Polypropylene	/	/
	Beam (prism)	12	10x10x40	4-point bending		/	/
[19]	Beam (segmented)	1	400 (span)	Bending under uniformly disturbed load	/	Manually placed	Post tensioning
[20]	Bridge	1	172x46x50	4-point bending	/	Cable (added by printer nozzle)	Post tensioning
	Bridge	1	344x92x650	Live load/reached 100% of SLS Moment in span	/	Cable (added by printer nozzle)	Post tensioning
[21]	Wall (with hollow section)	2	72x71x24	Axial compression	Polypropylene	/	/
		1	72x71x24			Manually placed	/
		2	120x71x24				/
		1	192x71x24				/
		2	240x71x24				/

Ref.	Type of element	Number of samples	Dimension of elements [cm]	Performed test	Type of fibers	Reinforcement	Cables
[22]	Beam (deep)	1	91x26x26	4-point bending	Polypropylene		/
	Beam (deep)	1	91x26x26			Manually placed	/
	Beam (deep)	1	91x26x26	3-point bending (eccentric)			/
[23]	Beam (segmented)	3	30x60x330	3-point bending	/	Manually placed	/
[3]	Beam (segmented)	1	20x45x300		Polypropylene	Manually placed	/

3 EXPERIMENTAL TESTING

As previously stated, the truss girder made by 3DCP was tested in a 4-point bending test. The mechanical properties and properties of fresh concrete were tested earlier [5].

3.1 The mix design for printed concrete

The 3D printed concrete truss girder was made from commercial ready-to-use one-component micro-concrete called Sikacrete®-751 3D, produced by Sika. The weight of a single bag of premix was 20 kg, which was sufficient enough to produce 13 liters of fresh concrete mixture. The premix components are: Portland cement, aggregate and some chemical additives, with maximum grain size of 1 mm [24]. The premix is mixed with water and two types of chemical additives: a High Range Water Reducer additive called Glenium and a Hydration Controller additive called MasterROC, manufactured by BASF. The quantity of all components for producing a fresh concrete mixture is shown in Table 2. The value of the water-binder ratio (w/b) was set at 0.15.

Table 2. Mixture design of fresh concrete for 3D printing

Material	Type	Manufacturer	Quantity [kg]
“Premix”	Sikacrete®-751 3D	SIKA	12.50
Glenium	HRWR	BASF	0.03
MasterROC	Hydration Controller	BASF	0.01
Water	Potable water	Water supply	1.88

The procedure for making a fresh concrete mixture had a few steps, which are described in Figure 2. The total mixing in the mixer time was 5.5 minutes. After mixing the fresh concrete, it was transported to the pump.

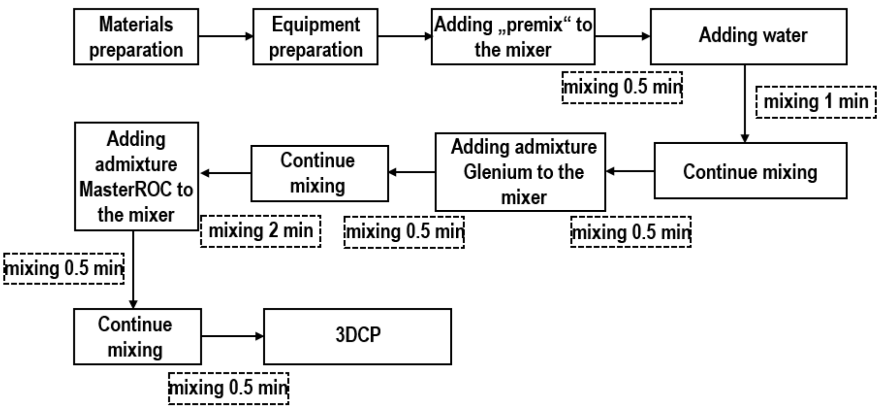


Fig. 2. Mixing procedure for fresh concrete for 3D printing

3.2 The description of the 3D printing process

The 3D concrete printing of the girder was performed in the Laboratory of Structures at the University of Belgrade’s Faculty of Civil Engineering, where the first 3D printer for concrete was installed in the Republic of Serbia [7]. The concept of a 3D printer is common to the CNC machine with the following parts (Figure 3.a.): an aluminum framework and a printing head that provides the movement of a hose with a circular nozzle (Figure 3.b.) with a diameter of 15 mm on the end. Unit for controlling printing head movement according to a G-code made from 3D model of printed elements and a pump, the PFT Swing-M, with a capacity of 20 bar and a maximum flow of 3 l/min, which provided conveying fresh concrete into the system. The printing head is able to move and rotate around all three axes (X, Y, and Z). The maximum speed in the X and Y directions is 6000 mm/min and 1500 mm/min in the Z direction. The printer is able to create specimens with maximal dimensions of 600x400x2500 mm.

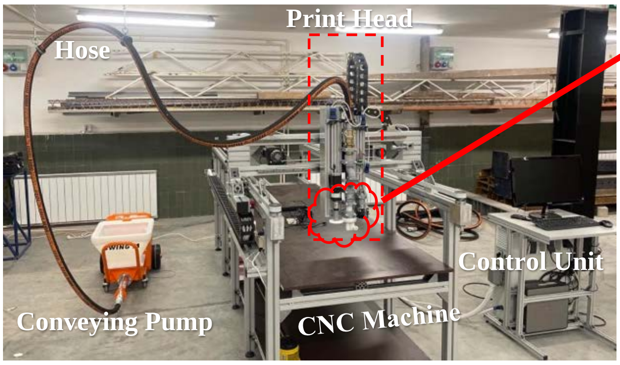
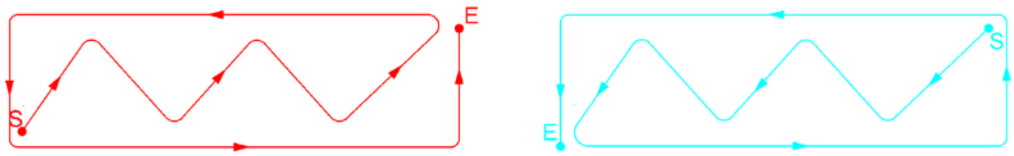


Fig. 3.a. The 3D concrete printer at the Faculty of Civil Engineering University of Belgrade [7]

Fig. 3.b. Circular nozzle used for printing

The printing process includes the alternating placement of two characteristic layers by moving the printer head in Z direction. The printing path for characteristic layers are shown on Figure 4. The movement speed of the print head was set at 1000 mm/min, while the pump pressure was 6.25 bar and the nozzle offset was 15 mm. The size of a printed element was 87x29x12 mm with layer widths of 50 mm. The total number of layers was eight, with a layer depth of 15 mm (Figures 5 and 6).



(a) (b)

Fig. 4. The printing path for the characteristic layer: (a) first, (b) second

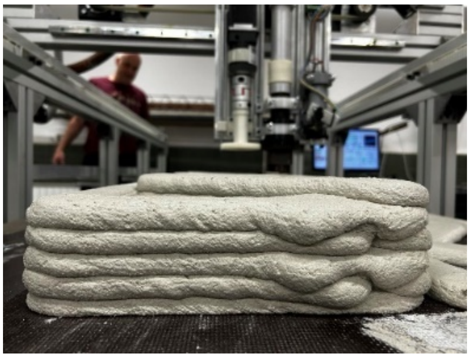


Fig. 5. Overlapping of characteristic layers

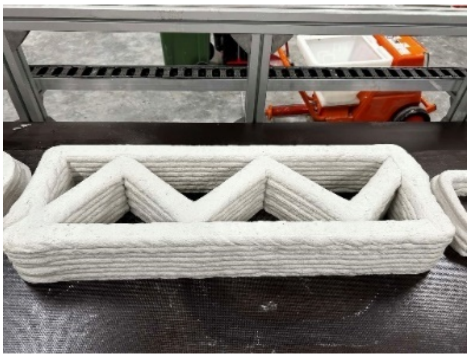


Fig. 6. 3D printed concrete girder

3.3 Experimental program

The experimental program in this research is divided into two parts: 1) testing of truss girder and 2) testing axial tension strength of the bottom and top chords.

1) The experimental setup for testing of truss girder is shown on Figures 7. Testing was performed on an Amsler press with a capacity of 2500 kN. The testing girder was set on fixed and movable (roller) supports with the addition of two L-profiles (dimensions 100x100x10 mm) to provide better support conditions. The testing force was applied to two nodes on the top chord over steel plates. The strain gauges PL-60-11 were set on one compressive and one tensile diagonal on both sides for measurement of strains. Strain gauges with labels m1 and m2 were set on the compressive diagonal, while m3 and m4 were on the tensile diagonal. Stress and forces in the diagonals are determined based on the measurement strain. The value of module of elasticity was adopted as 30 GPa. This value was determined from the correlation between the compressive strength of previously tested cubes [5] and concrete class C20/25. The dimension of cross section of diagonals was 12.5x5 cm. The vertical displacement of the bottom chord was measured with four LVDT sensors at two nodes on both sides of the girder. The LVDT sensors on the front side were labeled as U1 and U2, and on the back side as U3 and U4. The testing force was applied with an increment of 5 kN. The testing was recorded on the front and back sides of the girder with two FHD 1080P cameras.

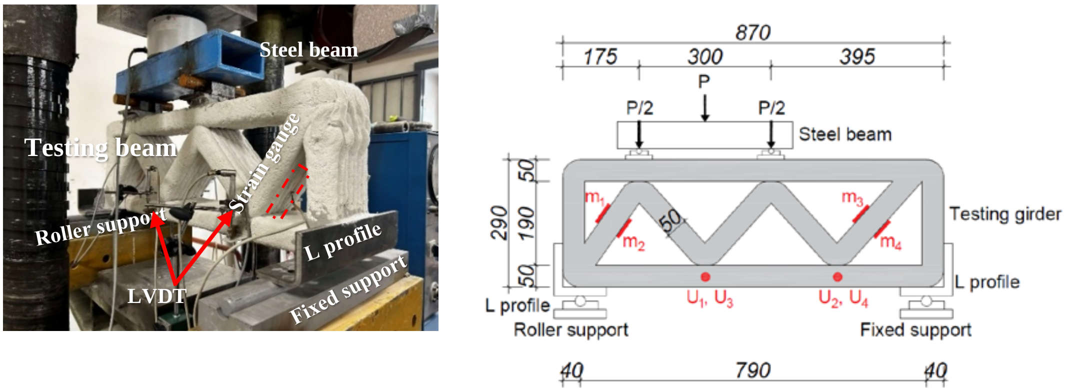


Fig. 7. Experimental setup for -point bending test

2) In the testing stage, samples were obtained from the bottom and top chords after the failure of testing girder. The total number of samples was three. The testing equipment was the Shimadzu AT-X universal testing machine with a capacity of 300 kN. To prepare the samples for testing, the treated surfaces were bonded to seals with an extension rod, which were then placed in the grips of the testing machine. The procedure for testing is similar to applied one in previous testing [5]. The rate of force increase during testing was 100 N/sec.

4 RESULTS AND DISCUSSION

The ultimate force that caused the girder failure was 30.10 kN. The displacement values at the moment of failure are shown in Table 3. It can be seen that the vertical displacement of both nodes was similar, with mean values of 0.56 and 0.57 mm. The same value of vertical displacement in both nodes indicated the same stiffness of nodes and bond between diagonals and chords, which is supported by a satisfying printing quality. The mean value of compressive force in the diagonal was 36.77 kN, for a tensile diagonal, the mean value was 13.45 kN. The layered structure of diagonals and different roughness of layers had an effect on the difference in value between strain gauges, and it was necessary to treat the diagonal surface for their gluing. Figures 8 and 9 show that the fracture of the girder occurred in the bottom chord, which is close to the roller support. The exceeding of the bearing capacity of the diagonal released the fracture and collapse of the system, which resulted in the splitting of the left part of the girder. Figure 10 shows the measured vertical displacement and forces in diagonals. The force in tensioned diagonal (TFD) is marked with the hidden lines and the force in compressive one (CFD) with continuous line.

The axial strength values of the bottom and top chords, the dimensions of the samples, and the values of the ultimate forces are presented in Table 4. The mean value of the axial strength is 3.84 MPa. Fracture patterns indicated that in all samples, the fracture occurred within the material and without delamination of layers. The fracture patterns and values of strength indicated satisfying printing quality, which indicated material homogeneity and the lower influence of layering on strength.

Fig. 8. The moment of reaching the ultimate bearing capacity

Fig. 9. Failure pattern of a 3D printed girder

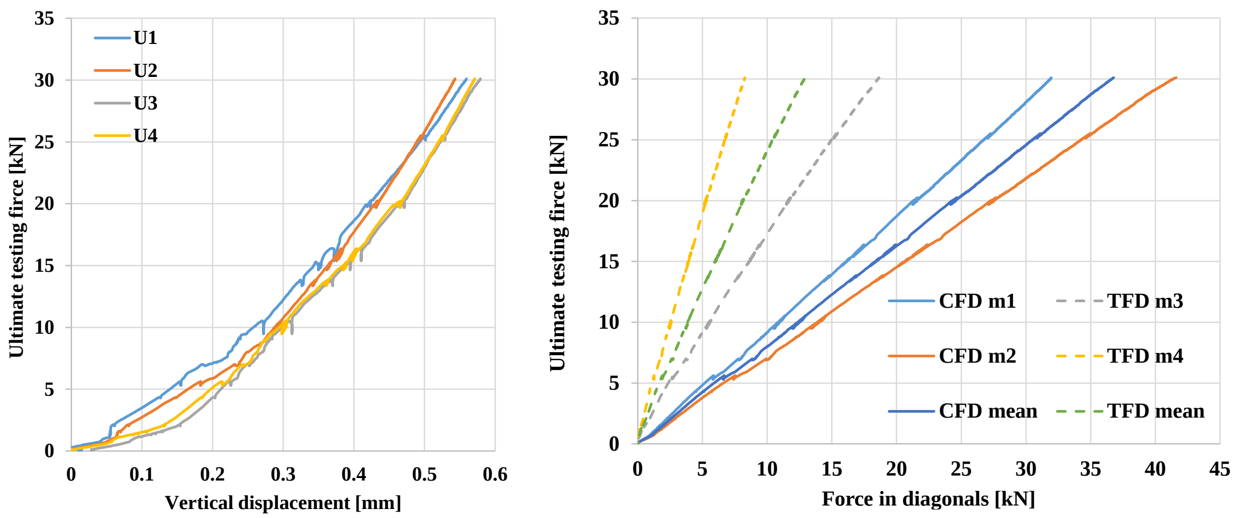


Fig. 10. (a) vertical displacements of the girder and (b) compressive and tensile forces in the chords of the girder

Table 3. The vertical displacement and forces in diagonals at failure

Ultimate Force Value [kN]	U_1 [mm]	U_3 [mm]	U_2 [mm]	U_4 [mm]	CFD m_1 [kN]	CFD m_2 [kN]	TFD m_3 [kN]	TFD m_4 [kN]
30.10	-0.56	-0.58	-0.54	-0.57	31.94	41.60	8.27	18.62
Average:	-0.57		-0.56		36.77		13.45	

Simplified numerical calculation showed the maximum tensile force was: in bottom chord 10.5 kN and TDF 12.4 kN. The measured TDF was 13.45 kN, that was greater than calculated one. According to the results shown in Table 4 tensile strength was 25.12 kN, this value is greater than the measured TDF. As was stated before the failure occurred in the near of rolled support where the stress state was not simple as the one in axial tensile test.

Table 4. The axial tension strength of samples

Label	Width [mm]	Length [mm]	Height [mm]	Area [mm^2]	Ultimate Force Value [kN]	Strength [MPa]
T-1	55.83	120.00	160.00	6699.60	25.96	3.90
T-2	55.80	122.80	160.00	6852.24	27.08	4.07
T-3	55.20	121.00	160.00	6679.20	22.31	3.55
Average value for axial tension strength:					25.12	3.84

5 CONCLUSIONS

From the performed tests and literature review the following conclusions can be made:

- The greater application of 3DCP technology is still limited because of the lack of design codes and guidelines. Also, tensile strains in real structures cannot be avoided, so the incorporation of reinforcement or tendons is necessary.
- The behavior of 3DCP structures was analyzed only for vertical loads (bending and axial compression of elements). There are no tests for lateral loads, and behavior of elements under serviceability limit states.
- Bearing capacity of tested girder was limited by the tensile strength of tensioned chord. Due to the fact that there were no added reinforcement or micro fibers in the mixture, the failure occurred in the tensioned chord.
- The same values of vertical displacement showed that there were no relative displacements between the layers. The difference between the force measured on two sides of same diagonal happened because of the different roughness of layers.
- Axial tension test showed that the connection between layers had capacity greater that the axial capacity of cross section. The failure occurred purely along the material without the delamination of layers.

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7 REFERENCES

[1] Menna, C., Asprone, D., Auricchio, F., Pulieri, S., & Rezaie, F. (2020). Opportunities and challenges for structural engineering of digitally fabricated concrete. *Cement and Concrete Research*, 133, 106079. https://doi.org/10.1016/j.cemconres.2020.106079

[2] Bhattacherjee, S., Basavaraj, A. S., Sanjayan, J. G., & Anand, A. (2021). Sustainable materials for 3D concrete printing. *Cement and Concrete Composites,* 122, 104156. https://doi.org/10.1016/j.cemconcomp.2021.104156

[3] Asprone, D., Auricchio, F., Menna, C., & Mercuri, V. (2018). 3D printing of reinforced concrete elements: Technology and design approach. *Construction and Building Materials*, 165, 218-231. https://doi.org/10.1016/j.conbuildmat.2018.01.018

[4] Hoffmann, M., Skibicki, S., Pankratow, P., Zieliński, A., Pajor, M., & Techman, M. (2020). Automation in the construction of a 3D-printed concrete wall with the use of a lintel gripper. *Materials*, 13(8), 1800. https://doi.org/10.3390/ma13081800

[5] Mitrović, S., & Ignjatović, I. (2023). Hardened properties of 3D printed concrete – Experimental investigation. Proceedings of the 20th Symposium of the Macedonian Association of Structural Engineers, Skopje, Republic of North Macedonia (pp. 1052–1064).

[6] Liu, W. G. K., Takasu, K., Jiang, J., & Zu, K. (2023). Mechanical properties of 3D printed concrete. Developments in the Built Environment.

[7] Ignjatović, I., Mitrović, S., Dragaš, J., & Carević, V. (2022). Application of 3D concrete printing technology. Proceedings of the 16th Congress of the Association of Structural Engineers of Serbia, Aranđelovac, Serbia (pp. 458–469).

[8] Khan, M. S., Sanchez, F., & Zhou, H. (2020). 3-D printing of concrete: Beyond horizons. *Cement and Concrete Research*, 133, 106070. https://doi.org/10.1016/J.CEMCONRES.2020.106070

[9] CNN Style. (2019). Shanghai opens world's longest 3D-printed concrete bridge. Retrieved from https://edition.cnn.com/style/article/shanghai-3d-printed-bridge-scli-intl/index.html

[10] COBOD. (2022, May 27). COBOD customer makes 3D printed tiny house. Retrieved from https://cobod.com/cobod-customer-makes-3d-printed-tiny-house/

[11] Gebhard, L., Esposito, L., Menna, C., & Mata-Falcón, J. (2022). Inter-laboratory study on the influence of 3D concrete printing set-ups on the bond behavior of various reinforcements. *Cement and Concrete Composites*, 133, 104660. https://doi.org/10.1016/j.cemconcomp.2022.104660

[12] Buswell, R. A., Leal de Silva, W. R., Jones, S. Z., & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research,* 112, 37–49. https://doi.org/10.1016/J.CEMCONRES.2018.05.006

[13] Sanjayan, J. G., & Nematollahi, B. (2019). 3D concrete printing for construction applications. 3D Concrete Printing Technology: Construction and Building Applications (pp. 1–11). https://doi.org/10.1016/B978-0-12-815481-6.00001-4

[14] Lyu F, Zhao D, Hou X, Sun L, Zhang Q. (2021). Overview of the Development of 3D-Printing Concrete: A Review. *Applied Sciences*. 2021; 11(21):9822. https://doi.org/10.3390/app11219822

[15] Avrutis, D., Nazari, A., & Sanjayan, J. G. (2019). Industrial adoption of 3D concrete printing in the Australian market: Potentials and challenges. 3D Concrete Printing Technology (pp. 389–409). https://doi.org/10.1016/B978-0-12-815481-6.00019-1

[16] Holt, C., Edwards, L., Keyte, L., Moghaddam, F., & Townsend, B. (2019). Construction 3D printing. 3D Concrete Printing Technology: Construction and Building Applications (pp. 349–370). https://doi.org/10.1016/B978-0-12-815481-6.00017-8

[17] Pfleger, M. P., Geyer, S., & Holzl, C. (2023). Investigation to improve the carbon footprint of thin-walled concrete structures by 3D printing prefabricated elements.

[18] Wang, L., Jiang, H., Li, Z., & Ma, G. (2020). Mechanical behaviors of 3D printed lightweight concrete structure with hollow section. *Archives of Civil and Mechanical Engineering,* 20(1). https://doi.org/10.1007/s43452-020-00017-1

[19] Vantyghem, G., De Corte, W., Shakour, E., & Amir, O. (2020). 3D printing of a post-tensioned concrete girder designed by topology optimization. Automation in Construction, 112, 103084. https://doi.org/10.1016/j.autcon.2020.103084

[20] Salet, T. A. M., Ahmed, Z. Y., Bos, F. P., & Laagland, H. L. M. (2018). Design of a 3D printed concrete bridge by testing. *Virtual and Physical Prototyping*, 13(3), 222–236. https://doi.org/10.1080/17452759.2018.1476064

[21] Han, X., Yan, J., Liu, M., Huo, L., & Li, J. (2022). Experimental study on large-scale 3D printed concrete walls under axial compression. *Automation in Construction*, 133, 103993. https://doi.org/10.1016/j.autcon.2021.103993

[22] Van den Heever, M., Bester, F., Kruger, J., & van Zijl, G. (2022). Numerical modeling strategies for reinforced 3D concrete printed elements. *Additive Manufacturing,* 50, 102569. https://doi.org/10.1016/j.addma.2021.102569

[23] Aramburu, A., Calderon-Uriszar-Aldaca, I., & Puente, I. (2023). Parametric modeling of 3D printed concrete segmented beams with rebars under bending moments. Case Studies in Construction Materials, 18, e01910. https://doi.org/10.1016/j.cscm.2023.e01910

[24] Sika. (2022). Sikacrete®-751/-752 3D one-component microconcrete 3D printing.

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