DOI: 10.31276/VJSTE.2024.0036

Design approaches proposed for bending components made by 3D concrete printers

Thi Loan Pham*

Department of Civil Engineering, Haiphong University, 71 Phan Dang Luu Street, Tran Thanh Ngo Ward, Kien An District, Hai Phong City, Vietnam

Received 15 April 2024; revised 27 May 2024; accepted 8 July 2024

Abstract:

The research and application of 3D printing technology in the construction industry have captured the attention of researchers, businesses, and management agencies. This innovative method of creating structures differs significantly from traditional construction methods and has the potential to revolutionise the field. However, it is crucial to ensure that the printed structures are safe when subjected to loads. This requires careful attention to the materials used, the printing process, and the structural design of the building. As a result, considerable research has been essential to develop standards and guidelines for designing, evaluating, and accepting printed concrete components and structures. This study addresses these issues by (1) providing an overview of the application of structural components made by 3D concrete printers; (2) analysing the behaviour of flexural reinforced concrete components; (3) categorising flexural printed components; and (4) proposing approaches to design printed components according to their category. This study concerns the behaviour of flexural components regarding 3D concrete printing technology. The design approaches for these components will be discussed, focusing on solid and hollow sections.

Keywords: **bending components, design approaches, flexural behaviour, hollow cross-section, solid cross-section, 3D concrete printing technology.**

Classification numbers: **2.1, 2.3**

1. Introduction

Concrete printing, also known as additive manufacturing, constructs 3D models layer by layer [1]. This technology, extensively researched, developed, and applied worldwide, is emerging as a transformative trend in the construction industry. It enables the production of building structures or components of various complexities, offering the advantages of reduced costs and accelerated construction times [2-6]. Moreover, automation and software technology have made 3D printing more effective. This technology is also considered environmentally sustainable because it can utilise various materials, including recycled materials and zero-waste additives, in the construction process [7].

This research begins with a 3D CAD model of the object, saved in ".STL" format. Then, Simplify3D software [8] was used to slice layers of the model and save it as a ".Gcode" file. Finally, 3D concrete printers controlled by Mach3 software [9] to print components. Fig. 1 illustrates this process.

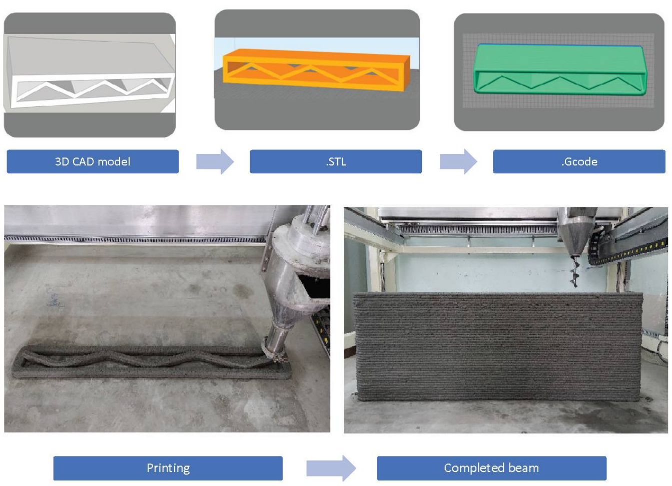


Fig. 1. Steps of the printing process [10].

*Email: loanpt297@gmail.com

(A) **Robot system** [11].

(B) **Gantry system** [12].

Fig. 2. Types of concrete printers.

Printing components or entire buildings with 3D printers can be implemented by gantry systems or robot systems, as shown in Fig. 2.

Similarly to traditional constructions, construction works with concrete printers can be done by printing whole buildings or assembling components. An entire project would require a large printer to print everything as per the designed model. However, outdoor conditions pose challenges in controlling the properties of the concrete, transporting and installing printers according to the project's location and dimensions, and other issues [13, 14]. It is worth mentioning that on-site printing of structures provides flexibility in terms of design for projects and leverages the remarkable benefits of 3D concrete printing technology from design to construction and labour [15]. In developed countries, printing the whole building is often preferred over assembling methods [16-18].

Dividing large projects into smaller components for printing is a promising solution for overcoming the limitations of large-sized printers. However, some potential issues arise when using this method as opposed to on-site printing:

- Determining the location of the project's subdivisions.

- Design and construction details of joints.

Nonetheless, printing components and assembling them, known as the inside printing method, also has some significant advantages:

- Printer size does not depend on project size.

- Laboratory construction conditions help better control the properties of the printed concrete.

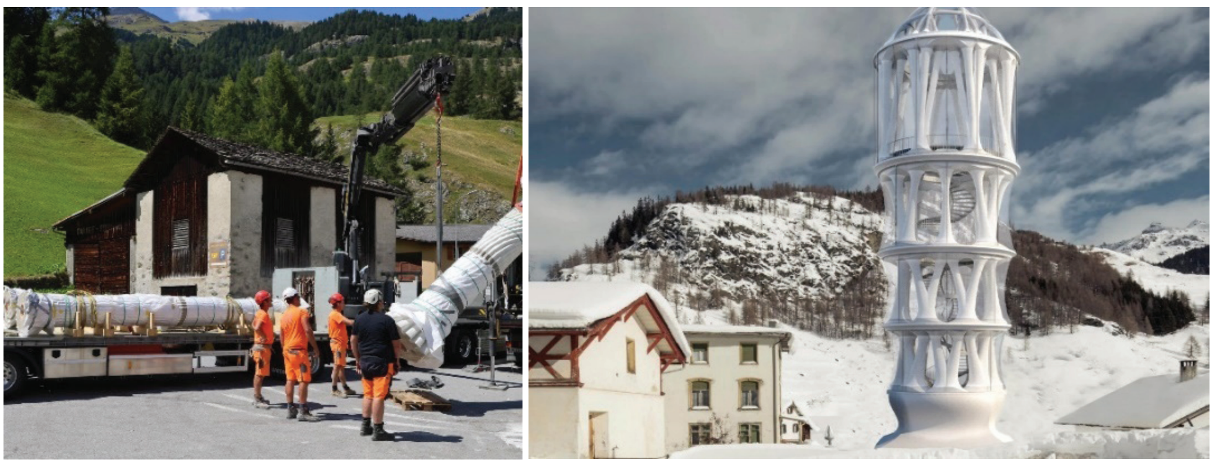
- Databases of printed concrete component types can be created for projects (sections, joints, working, etc.)

To understand the overall workings of a project, it is crucial to start by examining its parts. In traditional construction projects, the classification of structural systems and the study of their components have been the basis for standards for centuries. The last decade has seen significant research into the performance of components and projects for concrete printing, making it an excellent starting point for understanding their workings.

Numerous projects worldwide have been successfully printed and assembled using 3D technology [19, 20]. One of the most notable examples is the world's tallest tower in the Swiss village of Mulegns, set to be built in spring 2024. The 5-storey tower is primarily constructed of printed white concrete columns, with a total of 124 3D-printed components and 4,000 concrete layers as presented in Fig. 3. This innovative construction approach demonstrates the vast potential of 3D printing technology in building design and construction.

The level of research and application of components for printed concrete projects is necessary but quite complicated due to the diversity of cross-section types and component shapes. To suit the research conditions at Hai Phong University, the research team chose to

(A) Printing components.



(B) Transportation and erection.

Fig. 3. The world's tallest tower in Switzerland [19].

study the bending behaviour of printed concrete beam components. This is also the most essential component in the load-bearing structural system in a building, and the bending problem is considered a fundamental issue in general construction design.

Researching and applying components for printed concrete projects can be complex due to the diversity of cross-section types and component shapes. Based on the research conditions, this study focused on the flexural behaviour of printed concrete components. This is the most fundamental component in a building's load-bearing structural system, and the bending problem is a primary issue in general construction design. By studying this fundamental problem, the results provide valuable insights into the behaviour of printed concrete components in construction projects.

2. Behaviours of flexural reinforced concrete components in general

A flexural member is a structural component subjected to lateral loads, resulting in perpendicular loads to its axis. This causes the internal force components of bending moment and shear force. Consequently, the structure operates under the impact of moment and shear force. Based on the internal force components, the working states can be categorised as follows:

- Pure bending: Internal force components include only one moment.

- Flat bending: Internal force components include both moment and shear force.

In reality, the components in a project typically function in a flat-bending state. Depending on the load application diagram, the pure bending state only appears

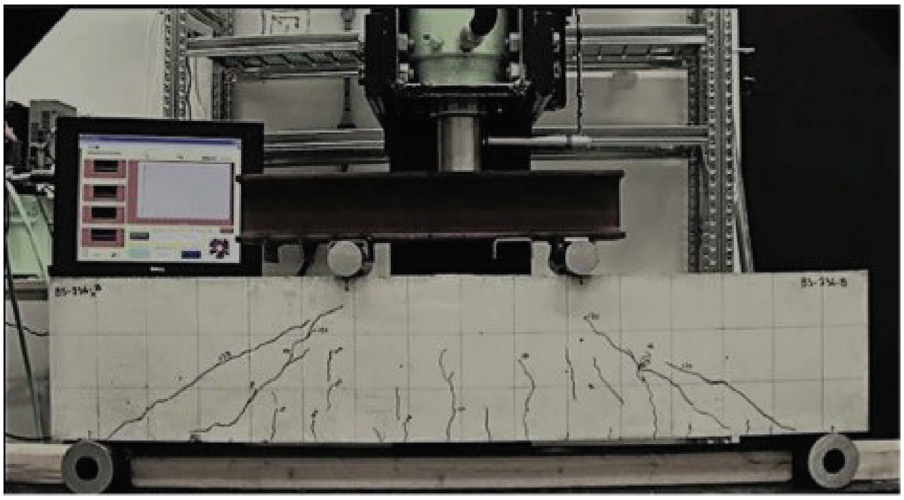


Fig. 4. Typical cracks in a bending test [21].

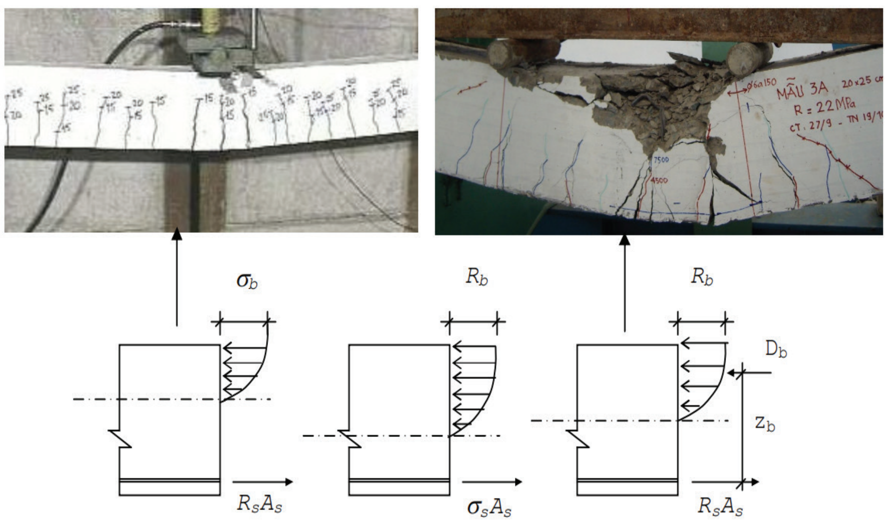


Fig. 5. Development of stress on the perpendicular section.

in specific parts of the structure, resulting in an internal force component of zero shear force. Therefore, studying the behaviour of a bending member's strength involves analysing the simultaneous bending and shearing behaviour of the sections along the axis of the member. To better understand the bending member's behaviour, a simple beam subjected to gradually increasing loads can be tested. When the load is small, the beam is intact with no cracks. As the load increases, cracks appear perpendicular to the beam axis in areas with a significant moment and inclined cracks in the area near the support where there is a sizeable shear force, as shown in Fig. 4. In the final stage, the beam can be damaged in the section with perpendicular cracks or the section with inclined cracks, depending on the reinforcement content in the beam.

Calculating beams based on strength is crucial to ensure they are not damaged on perpendicular or inclined sections. Strength calculations for perpendicular sections help prevent damage from bending forces, while strength calculations for inclined sections help avoid damage from shear forces. By considering both types of calculations, engineers can ensure that beams are designed to withstand all kinds of forces they may encounter in their intended use. The behaviour of bending members on perpendicular sections is considered under stress-strain development. On a perpendicular section, we can see that the tension cross-sectional area will gradually grow as the load increases, while the compression cross-sectional area will gradually narrow until the cross-section is considered destructive, as presented in Fig. 5.

In beam sections with large shear force, the normal stress due to moment and the tangential stress due to shear force may cause cracks to appear at an angle α to the beam axis, as shown in Fig. 6. Longitudinal and stirrup reinforcement passing through inclined cracks can resist failure along the inclined section. The failure is due to the moment tending to rotate the two parts of the beam around the compression zone while the shear force tends to pull them apart in a direction perpendicular to the beam axis. Despite this, design standards still separate the stirrups and diagonal reinforcement calculation according to shear force from the strength calculation on inclined sections.

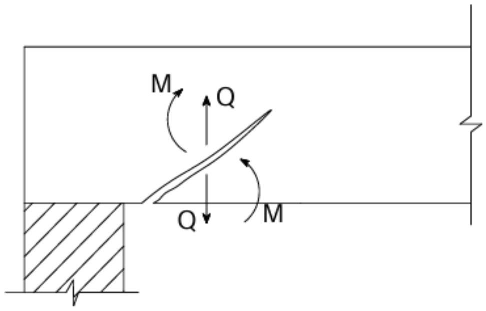


Fig. 6. Failure pattern by shear force.

When considering a bending concrete member as a frame element, moment and shear force control the behaviour of both traditional and printed components. However, the approach to studying printed concrete members will differ from that of conventional reinforced concrete members when examining the behaviour of perpendicular and inclined sections. The degree of difference in performance will depend on the section along the member axis. Therefore, developing new research for design calculations or building upon existing knowledge when working with printed components may be necessary.

3. Flexural components made by 3D concrete printers

Design principles for flexural components made of printed concrete depend on both cross-sectional geometry and reinforced methods. This research will propose a classification based on these principles (Fig. 7).

It is crucial to approach design principles by taking into account the following factors with utmost importance: the bending plane coincides with the printing plane and the bending plane is perpendicular to the printing plane.

It is common for structures with reinforcement, whether prestressed or not, to have an initial structural cross-section similar to traditional structural members with rectangular, I-shaped, or T-shaped shapes. This helps to ensure stability and strength in the overall structure. Design calculation theory used for conventional reinforced concrete bending components can confidently be applied to prestressed reinforcement in printed concrete structures, as the adhesion force is not a significant factor (Figs. 8A, 8B). However, the adhesion factor between the printed and poured concrete must be considered if voids are left when placing the reinforcement. Inheriting the traditional method of

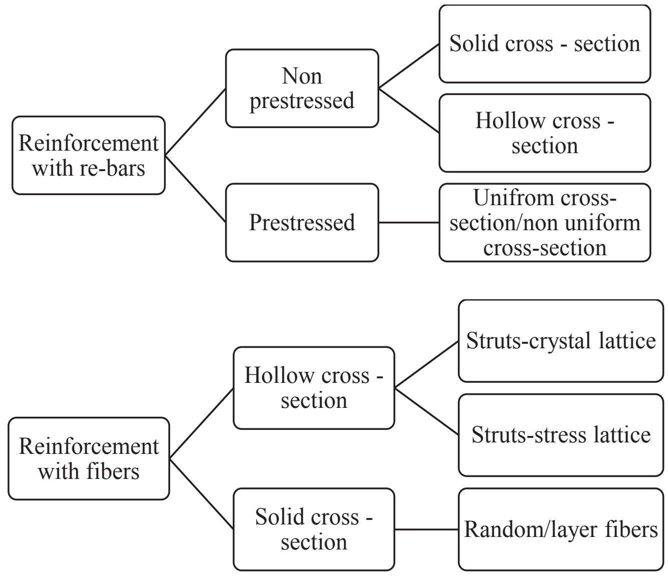
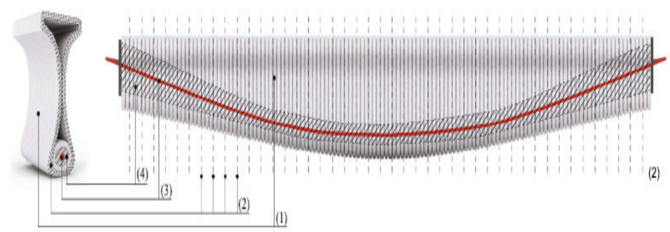
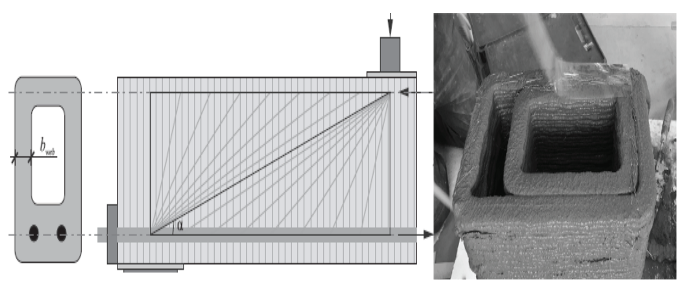


Fig. 7. Proposed categorisation of concrete printed components.



(A) Prestressed with non-uniform cross-section [22].



(B) Prestressed with uniform cross-section [22].

(C) Hollow cross-section [16].

Fig. 8. Printed components with rebar reinforcement.

calculating and designing reinforced concrete structures for printed concrete structures requires the addition of a safety factor or adjusting the section size based on the ratio of the void portion filled with concrete later (Fig. 8C). This approach ensures that the final structure is safe.

Research has shown that both forms of component printing can approach design principles without significantly affecting the results for printed components with reinforcement. This is because the reinforcement is placed in the tensile region of the structure, allowing for more flexibility in the printing process. However, further theoretical and experimental research must provide convincing results and recommendations.

The second method to reinforce materials is to use dispersed fibre. The popular fibres are glass, steel, and polyethylene, thanks to their positive effects on mechanical properties [23-25]. Dispersed fibre reinforcement can be introduced into printed concrete in two forms. The first form involves mixing the dispersed fibres with concrete and randomly dispersing them in the structure with a designed content. The second form strips the fibres into layers according to each layer of printed concrete, as shown in Fig. 9. This second form, as shown in Fig. 10, can be used for solid and hollow cross-sectional structures, but solid cross-sections are preferred. The layer cross-section must be large enough to ensure the fibres spread on the printed layers, usually a few millimetres long and randomly distributed. While the second form has its advantages, the first form is researched and applied more widely due to several outstanding benefits:

- No need to arrange two print heads for the same printer.

- Uniform printed concrete blocks for the entire structure.

- No separation of printed layers because the fibres create separate layers.

In addition to the advantages mentioned earlier, controlling the fibre content and length in dispersed fibre reinforcement is crucial to avoid clogging during printing.

In cases where reinforcement is not arranged in the structure, the printing plane is usually selected to coincide with the bending plane. The reasons are as follows:

- The connection of fibres dispersed in each printed layer will work better in the tensile region.

- The influence of the printed layers' adhesive force on the structure's working results is best limited.

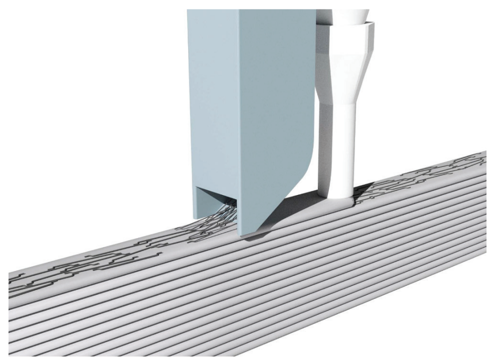


Fig. 9. Printed components reinforced with rebar [22].

(A) Crystal lattice struts [26].

(B) Stress lattice struts [22, 27].

Fig. 10. Hollow cross-section printed components.

When reinforcement is not arranged in a printed concrete structure, the printing plane is often selected to coincide with the bending plane. This is because:

- The connection among fibres dispersed in each printed layer works better in the tensile region.

- The designed model and printing process are more convenient.

4. Proposed design approaches

4.1. Solid cross-sections

For both the case of mixed fibres or fibres spread in layers, the principle of designing flexural members made of printed concrete is proposed according to the following assumptions:

- The material is non-homogeneous and anisotropic.

- Calculation principles designed according to material strength theory.

The non-homogeneous and anisotropic assumption is based on the different strengths of samples when subjected to loads in different directions induced by the layer interface [28-30]. Researchers conducted a series of tests, such as a tensile test, compression test, splitting test, and flexural test [13], which confirmed that 3DPC has apparent anisotropic behaviour compared to ordinary concrete. Its mechanical properties will be affected by the loading direction, printing direction, and printing parameters [31].

Strength conditions:

- Perpendicular section [32]:

$$\sigma_k = \frac{M}{W} \leq [\sigma_k] \quad (1)$$

where σ_k is the maximum tensile stress at the most dangerous section; M is the moment value at the dangerous section; W is the section modulus; $[\sigma_k]$ is the allowable stress corresponding to the failure state of the component determined from the experiment (sample bending test according to Vietnam Technical Standards (TCVN) 3119:2022 [33]).

- Inclined section [32]:

$$\tau = \frac{|Q_y|.S_x^c}{I_x.b^c} \leq [\tau] \quad (2)$$

where Q_y is the shear force acting on the bar; b^c is the actual width of the surface area at the point calculated by the tangential stress distribution; S_x^c is the static moment of the section limited by the actual width; I_x is the moment of inertia of the section; [τ] is the allowable shear stress.

Deformation condition:

$$f \leq [f] \quad (3)$$

where f is the member's deflection due to the load, calculated depending on the member's working diagram using methods in material strength, structural mechanics, or structural analysis applications such as SAP or ETABS; $[f]$ is the allowable deflection of bending members according to (TCVN) 5575:2012 [34] or other national codes.

4.2. Hollow cross-sections

Bending components with hollow cross-sections are becoming a popular design trend in concrete printing (Fig. 11). Digital manufacturing technology makes it technically and economically feasible to create structurally optimised components designed according to the principle of "shape contributed with stress contribution", also known as stress-based design [35]. This approach allows for the creation of structures that save materials, reduce the weight of components, and ultimately lower the weight of the entire building. Designing components with customised shapes, such as bending structures with hollow cross-sections, can be complex, and specific but complex-shaped structures can suffer from severe stress and strain localisation problems beyond the scope of current structural design standards [36]. While many components and structures have been printed, the commercial application of 3D printing in construction has been slow due to its insufficient structural safety [37]. Moreover, modelling such components requires technical and analytical skills from the designer and software supporting structural analysis. However, with increasing computing power, there has been a significant increase in the number of numerical models available to predict and improve the structural performance of concrete structures. Despite the challenges involved, this has made it easier to calculate and design components with complex shapes.

Depending on the shape, printers can make two hollow cross-section components: crystal lattice and stress lattice, according to the author's suggestion. Within the scope of the study, the crystal lattice is understood to have representative units that are repeated according to rules. In studying printed concrete structures, a crystal lattice is a repeating pattern of representative units that follow specific rules. These units can come in various shapes and sizes, such as cubes, stars, hexagons, diamonds, etc. By combining these shapes, designers can create specific lattice structures for their systems. The size of the lattice unit is determined by adjusting the thickness and length of the components and connecting nodes. Higher repetition density leads to smaller and more complex crystal lattices. While larger cells can be easily printed, the geometrical uniformity across any component cross-section will be lower.

To design crystal lattice structures, it is essential to follow a preliminary approach proposed through the process presented in Fig. 12.

Analysing the numerical model of the behaviour of printed concrete components is an important and complex step (Steps 3 and 4). The design principle for perpendicular or inclined sections for traditional solid or hollow members will be challenging because the material distribution on perpendicular or inclined sections varies with location. The design of crystalline printed concrete components will depend on stress analysis of each cross-section at each different material distribution area to check the conditions in Step 5. Equations (1), (2), and (3) give the conditions of strength and deformation. The difference is that these checking conditions apply to each crystal lattice member. By following this approach, you can design crystal lattice structures that are visually appealing and structurally sound.

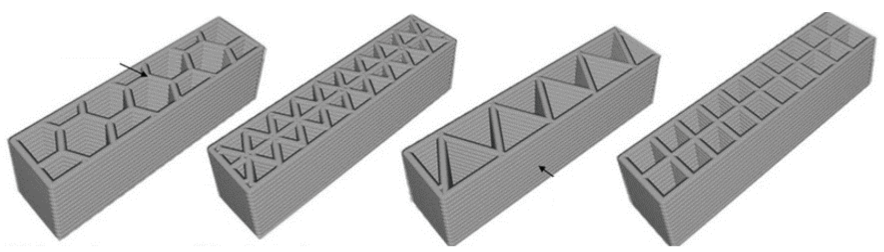


Fig. 11. Bending components with crystal lattice struts [38].

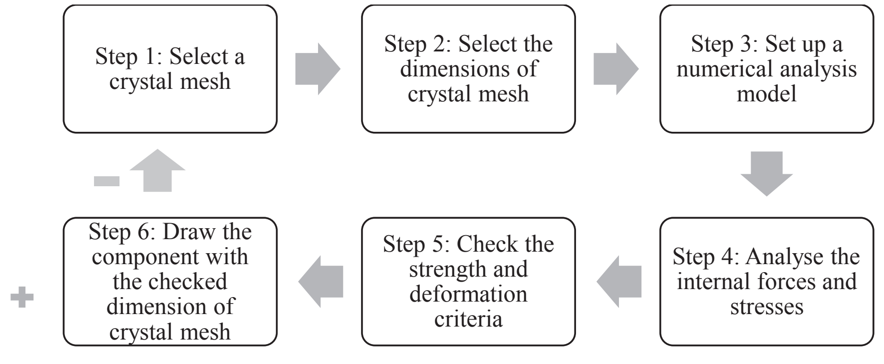
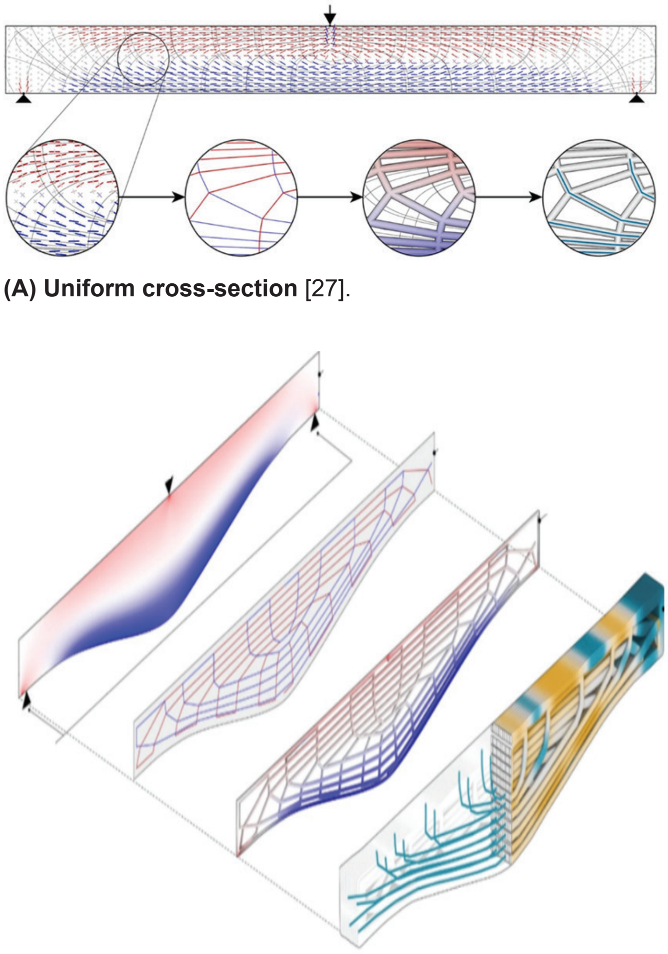


Fig. 12. Design process proposed for crystal lattice structures.

A component printed in the form of a stress lattice is a structure printed according to the tensile and compressive stress fields distributed in the structure when subjected to load. The lattices forming the components are printed according to the stress isostatic



(A) Uniform cross-section [27].

(B) Non-uniform cross-section [39].

Fig. 13. Stress distribution inside the bending components.

curves, which are the orthogonal pairs of curves representing the trajectory of internal forces in each load impact diagram. These curves indicate the directions in space where the stress is purely axial, and sections oriented along the principal stress direction are not subjected to any shear or bending stresses. This printing method is used to reduce the weight of structural elements and increase structural efficiency. Fig. 13 illustrates the number of flexural members printed according to the stress lattices.

The analysis of structural behaviour and the process of designing and manufacturing stress lattice components is a highly elaborate and complex task that requires advanced techniques. This process is more intricate than the problem of designing crystal components, as it involves analysing the distribution of tensile and compressive stresses in the structure when subjected to force. The design and manufacturing process of stress lattice components involves printing lattice lines according to the stress isostatic curves, which requires high precision and expertise. This is necessary to ensure the resulting structure is structurally sound and can withstand potential stress. To design stress lattice structures, a preliminary approach can be proposed in the following process, as shown in Fig. 14.

For such structures, numerical models will be analysed two times. The first time, the distribution of stress of the behaviour of printed concrete components with solid cross-sections will be found (Step 2). Then, the filament details of the longitudinal section will be designed using experience. A numerical model of stress lattice components will be carried out (Step 3) to get the results of stress and internal forces (Step 4). Equations (1), (2), and (3) also give the conditions of strength and deformation. The difference is that these checking conditions apply to each stress lattice filament.

In addition to the previously mentioned approaches to designing flexural printed concrete members, the study utilises an experimental design approach known as "Design by testing" [40, 41]. This approach is becoming increasingly popular for printed concrete structures as design calculation theory is still forming. The author has conducted experimental investigations, as shown in Fig. 15, on the flexural behaviours with triangle lattice structures [10, 26].

The failure pattern and cracked surfaces of all printed triangle lattice components indicate that the adhesion force between the printed layers ensures the overall working of the structure. The results prove good capacity by considering the flexural strength, bending stiffness, ductility, and compressive strength of concrete reinforced

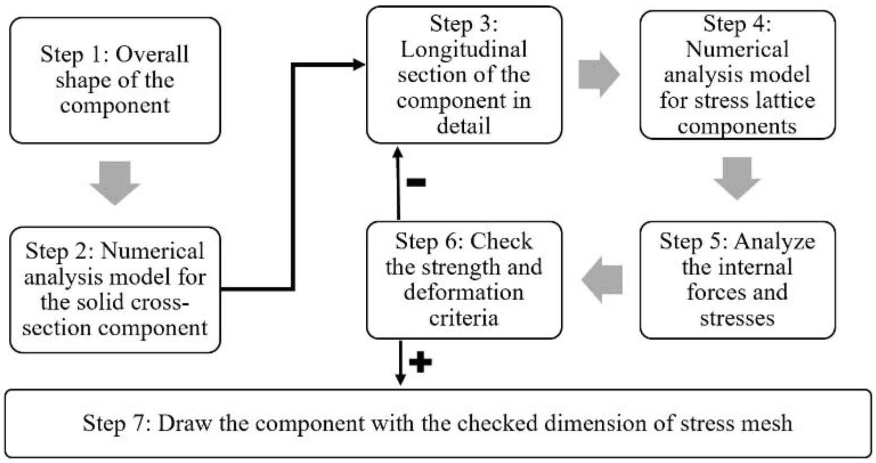


Fig. 14. Design process proposed for stress lattice structures.

Fig. 15. Flexural test of triangle lattice model.

with fibres. By conducting experiments and analysing the resulting data, researchers can gain valuable insights into the behaviour of printed concrete components and use this information to refine and improve the design methods.

5. Conclusions

After analysing the behaviour of bending members in general, as well as printed members, it can be concluded that 3D concrete printing is a promising technology for the production of complex concrete structures. This technology has the potential to reduce the use of formwork, increase the accuracy of concrete placement, and enable the fabrication of structures with intricate geometries. However, further research is needed to fully understand the behaviour of 3D-printed concrete components under different loading conditions and to optimise the printing process for various applications. Overall, 3D concrete printing has the potential to revolutionise the construction industry and offer new opportunities for architects, engineers, and designers.

Research on the structural behaviour of 3D-printed components is crucial for their successful application in building structures. In particular, the category of bending printed components can be chosen for efficient designing methods. The printing plane is often selected to coincide with the bending plane to take advantage of the connection among fibres dispersed in each printed layer, the convenient printing process, and the designed model. When designing the solid cross-section of a bending component, material strength theory can be used based on homogeneous and anisotropic assumptions. The design process for struts crystal lattice components can be followed by the approach proposed, which consists of four steps. Similarly, the design process for struts stress lattice components can be followed by the approach proposed, which consists of five steps. In the formation stage, the design approach known as "Design by testing" is popular. This approach involves testing the printed components and adjusting the design based on the results to ensure that the final structure meets the required safety standards. Overall, research on the structural behaviour of 3D-printed components is vital for their successful application in building structures, and careful design and testing are necessary to ensure their safety and efficiency.

ACKNOWLEDGEMENTS

The authors would like to acknowledge financial support from Hai Phong University (DTTD.2024.01), and material support from Thanh Hung Concrete Joint Venture Company.

COMPETING INTERESTS

The author declares that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] R. Kawalkar, H.K. Dubey, S.P. Lokhande (2022), "A review for advancements in standardization for additive manufacturing", *Mater. Today Proc.*, **50(5)**, pp.1983-1990, DOI: 10.1016/j.matpr.2021.09.333.

[2] L. Stinson (2019), "World's largest 3D-printed building completed in Dubai", *Curbed*, https://archive.curbed.com/2019/12/30/21035765/world-largest-3d-printed-building-dubai-apis-cor, accessed 10 January 2024.

[3] L. Alter (2018), "3D printed house displayed at Milan Design Week", *Treehugger*, https://www.treehugger.com/green-architecture/3d-printed-house-displayed-milan-design-week.html, accessed 10 January 2024.

[4] 3dsourced (2024), "ICON & new story 3D printed house in Austin, Texas USA", https://3dsourced.com/guides/3d-printed-house-2/#4_ICON, accessed 25 February 2024.

[5] S. Saunders (2022), "Robotic 3D printed Yhnova house officially inaugurated, tenants to move in soon", *3DR Holding*, https://3dprint.com/207936/3d-printed-yhnova-house-done/, accessed 24 January 2024.

[6] A. Frearson (2014), "Chinese company 3D prints 10 buildings in a day using construction waste", *Dezeen*, https://www.dezeen.com/2014/04/24/chinese-company-3d-prints-buildings-construction-waste/, accessed 24 January 2024.

[7] J. Nilimaa (2023), "Smart materials and technologies for sustainable concrete construction", *Dev. Built Environ.*, **15**, DOI: 10.1016/j.dibe.2023.100177.

[8] Simplify3D (2024), "Simplify3D desktop software", https://www.simplify3d.com/, accessed 24 January 2024.

[9] Goodwin University (2024), "Mach3 CNC control software", https://www.goodwin.edu/glossary/mach-3-cnc-control-software, accessed 24 January 2024.

[10] T.L. Pham, D.T. Trinh, T.H.T. Nguyen, et al. (2023), "Study on flexural behaviour of printed concrete wide beams using polypropylene fibres", *Vietnam Journal of Science, Technology and Engineering - MOST*, **65(4)**, pp.48-53, DOI: 10.31276/vjste.65(4).48-53.

[11] L. Grozdanic (2017), "Giant robots are building a futuristic house in Switzerland", *Inhabitat*, https://inhabitat.com/giant-robots-and-3d-printers-are-building-a-futuristic-house-in-switzerland/, accessed 24 January 2024.

[12] Cobod (2024), "Cobod products", https://cobod.com/, accessed 24 January 2024.

[13] P.S. Ambily, S.K. Kaliyavaradhan, N. Rajendran (2024), "Top challenges to widespread 3D concrete printing (3DCP) adoption - A review", *Eur. J. Environ. Civ. Eng.*, **28(2)**, pp.300-328, DOI: 10.1080/19648189.2023.2213294.

[14] A.S. Rao, M. Radanovic, Y. Liu, et al. (2022), "Real-time monitoring of construction sites: Sensors, methods, and applications", *Autom. Constr.*, **136**, DOI: 10.1016/j.autcon.2021.104099.

[15] H. Tu, Z. Wei, A. Bahrami, et al. (2023), "Recent advancements and future trends in 3D concrete printing using waste materials", *Dev. Built Environ.*, **16**, DOI: 10.1016/j.dibe.2023.100187.

[16] M. Alawneh, M. Matarneh, S. El-Ashri (2018), "The world's first 3D-printed office building in Dubai", *PCI/NBC*, https://www.pci.org/PCI_Docs/Papers/2018/32_Final_Paper.pdf, accessed 24 January 2024.

[17] Cobod (2022a), "The largest 3D printed building project in the US", https://cobod.com/the-us-largest-3d-printed-building-project/, accessed 24 January 2024.

[18] Cobod (2022b), "The tallest 3D printed building in the world is now in Saudi Arabia", https://cobod.com/the-worlds-tallest-3d-printed-building-is-now-in-saudia-arabia/, accessed 24 January 2024.

[19] Swisstech (2024), "A tower from a 3D printer", https://www.swiss.tech/news/tower-3d-printer, accessed 18 March 2024.

[20] R. Wolfs, D. Bos, T. Salet (2023), "Lessons learned of project Milestone: The first 3D printed concrete house in the Netherlands", *Mater. Today Proc.*, DOI: 10.1016/j.matpr.2023.06.183.

[21] D.W. Harris (2018), "Steel fibres and concrete flexural strength", *Inforce*, https://www.inforceglobal.com/steel-fibres-and-concrete-flexural-strength/, accessed 18 March 2024.

[22] L. Gebhard, J.M. Falcón, A. Anton, et al. (2021), "Structural behaviour of 3D printed concrete beams with various reinforcement strategies", *Eng. Struct.*, **240**, DOI: 10.1016/j.engstruct.2021.112380.

[23] A.A. Jhatial, S. Sohu, N.K. Bhatti, et al. (2018), "Effect of steel fibres on the compressive and flexural strength of concrete", *Int. J. Adv. Appl. Sci.*, **5(10)**, pp.16-21, DOI: 10.21833/ijaas.2018.10.003.

[24] D. Sinha, A. Verma (2017), "Investigation on the effect of varying dosages of steel fibre on the strength and workability properties of high strength concrete", *ICRISET2017. International Conference on Research and Innovations in Science, Engineering and Technology. Selected Papers in Civil Engineering*, pp.352-356, DOI: 10.29007/rjbd.

[25] I. Hussain, B. Ali, T. Akhtar, et al. (2020), "Comparison of mechanical properties of concrete and design thickness of pavement with different types of fiber-reinforcements (steel, glass, and polypropylene)", *Case Stud. Constr. Mater.*, **13**, DOI: 10.1016/j.cscm.2020.e00429.

[26] L.T. Pham, T.D. Trinh, Q.T. Do, et al. (2023), "Flexural behavior of printed concrete wide beams with dispersed fibers reinforced", *Res. Eng. Struct. Mater.*, **10(2)**, pp.727-742, DOI: 10.17515/resm2023.19me0925rs.

[27] L. Breseghello, R. Naboni (2022), "Toolpath-based design for 3D concrete printing of carbon-efficient architectural structures", *Addit. Manuf.*, **56**, DOI: 10.1016/j.addma.2022.102872.

[28] B. Panda, S.C. Paul, M.J. Tan (2017), "Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material", *Mater. Lett.*, **209**, pp.146-149, DOI: 10.1016/j.matlet.2017.07.123.

[29] G. Ma, Z. Li, L. Wang, et al. (2019), "Mechanical anisotropy of aligned fiber reinforced composite for extrusion-based 3D printing", *Constr. Build. Mater.*, **202**, pp.770-783, DOI: 10.1016/j.conbuildmat.2019.01.008.

[30] T. Ding, J. Xiao, S. Zou, et al. (2020), "Anisotropic behavior in bending of 3D printed concrete reinforced with fibers", *Compos. Struct.*, **254**, DOI: 10.1016/j.compstruct.2020.112808.

[31] P. Zarean, P. Malgaroli, P. Zarean, et al. (2023), "Effect of printing parameters on mechanical performance of material-extrusion 3D-printed PEEK specimens at the point-of-care", *Appl. Sci.*, **13(3)**, DOI: 10.3390/app13031230.

[32] G. Mendes, B. Lago (2009), *Strength of Materials*, Nova Science Publishers, 272pp.

[33] Vietnam Ministry of Science and Technology (2022), *TCVN 3119:2022 on Hardened Concrete - Test Method for Flexural Tensile Strength* (in Vietnamese).

[34] Vietnam Institute for Building Science and Technology (2018), *TCVN 5574:2018 on Design of Concrete and Reinforced Concrete Structure*, Construction Publishing House, 198pp (in Vietnamese).

[35] J.H. Vargas (2023), *Design for 3D Concrete Printing: Optimisation Through Integrated Workflows*.

[36] T.Y.P. Yuen, T.H. Wen, C.C. Hung, et al. (2022), "An eigendecomposition-based and mesh-sensitivity reduced constitutive model for nonlinear analysis of concrete structures under non-proportional cyclic loading", *J. Build. Eng.*, **47**, DOI: 10.1016/j.jobe.2021.103875.

[37] K. Liu, K. Takasu, J. Jiang, et al. (2023), "Mechanical properties of 3D printed concrete components: A review", *Dev. Built Environ.*, **16**, DOI: 10.1016/j.dibe.2023.100292.

[38] D. Liu, Z. Zhang, X. Zhang, et al. (2023), "3D printing concrete structures: State of the art, challenges, and opportunities", *Constr. Build. Mater.*, **405**, DOI: 10.1016/j.conbuildmat.2023.133364.

[39] L. Breseghello, H. Hajikarimian, H.B. Jørgensen, et al. (2023), "3DLightBeam+. Design, simulation, and testing of carbon-efficient reinforced 3D concrete printed beams", *Eng. Struct.*, **292**, DOI: 10.1016/j.engstruct.2023.116511.

[40] G. Monti, S. Alessandri, S. Santini (2009), "Design by testing: A procedure for the statistical determination of capacity models", *Constr. Build. Mater.*, **23(4)**, pp.1487-1494, DOI: 10.1016/j.conbuildmat.2008.07.016.

[41] G. Sedlacek, C. Müller (2008), "Eurocode - EN 1990 basis of structural design", *Design*, pp.18-20.