Analytical Study on 3D-Printed Concrete Wall with Different Wall Configurations When Exposed to High Temperature

B. Vignesh and N. Parthasarathi

1 Introduction

Concrete is one of the most widely used modern building materials. Three-dimensional-printed concrete is a relatively new concept that has been getting more attention in recent times. The concrete mixture used here consists of water, cement, and aggregates, which is designed to be easily extruded through the nozzle of the 3D-printing equipment. The structures are built with the concept of layering where a layer will be deposited on a previously poured layer repeatedly until the required structure is formed. Firstly, a model will be created, and then, the co-ordinates will be converted into code and that will be fed into the 3D printer. Using 3D-printed concrete is cost-effective as it eliminates the need for casting concrete into molds or framework. The need for intensive labor is avoided in this process, and complex geometric structures can be easily created within a tight schedule with minimal chances of human error. It also helps in reducing construction waste, which makes it environmentally friendly. Three-dimensional-printed concrete can achieve a curing time as short as three days, allowing for the rapid construction of entire structures within hours, making it time efficient. These factors help us to understand that the 3D-printed concrete is a relatively quicker and cheaper alternative to conventional concrete. Paul et al. [1] talked about the advantages of the 3D-printed concrete and the materials that are used. One of the major advantages is that it is easier to design even the complex geometries rapidly. Fine particles are used significantly in 3DPC, but the coarse aggregates are not generally used. The most commonly used materials are cement, sand, water, fly ash, silica fume, super plasticizer, and fiber particles additionally to improve the tensile strength and toughness of 3DPC. Lyu et al. [2] explained the basic principles and process of concrete 3D-printing technology and

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O. Gencel et al. (eds.), *Sustainable Innovations in Construction Management*, Lecture Notes in Civil Engineering 388, https://doi.org/10.1007/978-981-99-6233-4_46

also give detailed review of the material properties. The mechanical properties of the 3D-printed concrete are in research and development stage, and hence, it can be used for low-rise buildings but cannot be used for high-rise buildings in one print, but the parts can be printed separately and later assemble it, like pre-fabricated buildings. Only high strength concrete can be used in 3DPC for more strength, ordinary cement which cannot meet the requirements for the performance of the building. Adding fiber to the 3DPC will help in increasing the tensile strength and the toughness. A numerical model was developed by Wolfs et al. [3] to analyze the behavior of 3D-printed concrete. The model focused on studying the linear stress–strain relationship of the material until failure occurred. In order to obtain the necessary material properties, compression tests and direct shear tests were conducted. The findings revealed that as the fresh concrete ages, there is a linear increase in both Young's modulus and cohesion. However, the Poisson's ratio remained constant at 0.3, which was determined from the lateral deformations observed during the compression test, while the angle of internal friction also remained unchanged. In a study conducted by Suntharalingam et al. [4], the performance of different types of 3D-printed concrete walls, including solid, cavity, and composite walls, was examined in relation to their behavior under fire. The findings indicated that when exposed to standard fire conditions, non-load-bearing cavity walls made of 3D-printed concrete did not exhibit as good performance as solid 3D-printed concrete walls. EN 1992-1-2 [5] provides details about the thermal properties of concrete that incorporates siliceous and calcareous aggregates at elevated temperatures. This includes information on thermal conductivity, specific heat, and density. Marais et al. [6] analyzed the performance of high strength concrete and lightweight foam concrete under high temperatures. The results showed that the materials with high thermal conductivity perform well as 3DPC wall and the ones with lower thermal conductivity perform better as normal solid wall, and 3D-HSC wall performs better than HSC solid wall, whereas LWFC solid wall performs better than 3D-LWFC wall. Suntharalingam et al. [7] studied the fire performance of 20 different 3DPC wall configurations using finite element models, specifically evaluating their response under standard fire conditions. The study's results highlighted that 3D-printed concrete (3DPC) non-load-bearing cavity walls show considerable resistance when exposed to standard fire loads. Notably, there was a noteworthy enhancement in fire performance by increasing the thickness of the walls arranged in parallel rows. These non-load-bearing cavity walls exhibited impressive resistance for a duration of four hours under standard fire load conditions.

2 Modeling

The dimension considered for the 3D-printed models has been provided in Table 1.

Table 1 Modeling and dimensions data

Description	Values
Length of the wall	1000 mm
Depth of the wall	100 mm
Height of the wall	500 mm
No. of layers	50 layers
Layer thickness	10 mm
Mesh size	25 mm

3 Finite Element Analysis

The finite element modeling for multiple 3D-printed concrete walls with and without openings was modeled using ABAQUS. The software was used to analyze the loaded 3D-printed concrete walls at high temperature, and the displacement and stresses were also studied by exposing the model to fire conditions.

3.1 Properties and Specimen Details

The dimensions of the 3DPC wall are 1000 mm length, 500 mm width, and 100 mm depth. The 3D-printed concrete wall has 50 layers with each layer having the 10 mm layer thickness. Properties such as conductivity, specific heat, Young's modulus, and mass density are given in Table 1 as per the EN 1992-1-2 [5] which provides the thermal properties at elevated temperature. The properties obtained were slightly modified as per Suntharalingam [7]. Totally, 16 sets of 3DPC walls are there with square, circular, rectangular, triangular, and hexagonal openings. The material and thermal properties are provided in Table 2, and the specimen details are provided in Table 3.

The top surface of the various types of 3D-printed concrete wall models is shown in Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16.

3.2 Modeling and Meshing

The part was created and then assembled using the method of layering with 50 layers and layer thickness of 10 mm. Tie interaction and film coefficient were provided using EN ISO 6946 [8]. The model was analyzed for the time period of 2 h or 7200 s. Pressure was created on the top surface of the wall, and the surface heat flux was applied on the front surface of the wall as per ISO-834-10:2014 [9]. The bottom side of the 3DPC wall is fixed. In the fixed boundary condition, the displacement and the rotation in the x, y, and z directions (U1, U2, U3, UR1, UR2, UR3) are zero. The film

Table 2 Material and thermal properties

Temperature (°C)	Conductivity (W/m K)	Mass density (N/mm^2)	Specific heat (J/kg K)	Young's modulus (N/mm^2)
23	1.95	2.40E−09	600	27,368.16
100	1.77	2.40E−09	900	27,368.16
200	1.55	2.35E−09	1000	26,016.82
300	1.36	2.32E−09	1050	23,278.2
400	1.19	2.28E−09	1100	20,539.59
500	1.04	2.26E−09	1100	16,431.67
600	0.91	2.24E−09	1100	12,323.75
700	0.81	2.22E−09	1100	8215.83
800	0.72	2.20E−09	1100	4107.91

Table 3 Details of specimen

Model number	Model name	Opening name	No. of openings
1	Solid wall	–	–
2	BS1	Square	5
3	BS2	Square	10
4	BS3	Mini-square	10
5	BS4	Mini-square	20
6	BT1	Triangle	5
7	BT2	Triangle	10
8	BT3	Mini-triangle	10
9	BT4	Mini-triangle	20
10	BT5	Truss	21
11	BH1	Hexagon	5
12	BH2	Hexagon	10
13	BR1	Rectangle	5
14	BR2	Mini-rectangle	10
15	BR3	Mini-rectangle	20
16	BHT1	Hexagon and triangle	28

Fig. 1 Solid wall

Fig. 2 BS1 wall

Fig. 3 BS2 wall

Fig. 4 BS3 wall

Fig. 5 BS4 wall

Fig. 6 BT1 wall

Fig. 7 BT2 wall

Fig. 8 BT3 wall

Fig. 9 BT4 wall

Fig. 10 BT5 wall

Fig. 11 BH1 wall

Fig. 12 BH2 wall

Fig. 13 BR1 wall

coefficient was applied as per EN ISO 6946:2017 [8]. Here, coupled temperature–displacement analysis has been carried out in the transient state. By implementing the convergence study, optimum mesh size of 25 mm was determined and applied to all the models as shown in Fig. 2. Eight-node brick element has been used as it can yield more precise outcomes and handle irregular shapes with minimal compromise in accuracy (Figs. 17 and 18).

Fig. 14 BR2 wall

Fig. 15 BR3 wall

Fig. 16 BHT1 wall

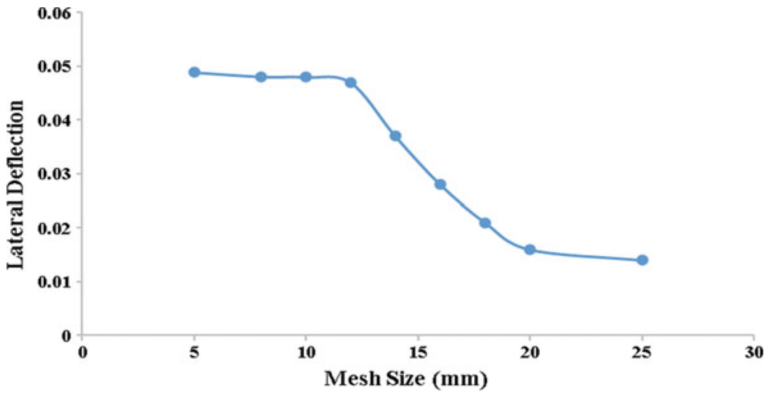

Fig. 17 Convergence study for optimum mesh size

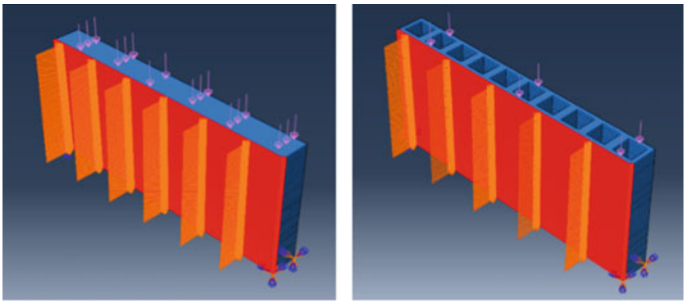

Fig. 18 Surface heat flux and pressure applied on solid wall and BS2

4 Results and Discussion

4.1 Results

The results of the finite element study on loaded 3D-printed concrete wall are provided below, and multiple graphs are were modeled to study the behavior of the 3DPC wall under pressure and surface heat flux. The results obtained are provided in Table 4.

Table 4 Results obtained

Model name	Temperature (°C)	Displacement (mm)	Shear stress (N/mm^2)
Solid wall	922	3.2	1.8
BS1	891	2.78	1.46
BS2	877	2.02	1.01
BS3	811	2.04	1.57
BS4	839	2.6	1.76
BT1	826	2	1.43
BT2	759	1.37	1.62
BT3	784	1.72	1.8
BT4	806	1.87	1.77
BT5	836	1.57	0.98
BH1	837	2.41	1.44
BH2	792	1.72	1.26
BR1	909	1.65	0.92
BR2	878	2.65	1.17
BR3	867	2.1	1.06
BHT1	760	1.33	1.15

4.2 Discussion

The time versus temperature curve for 3DPC concrete wall is given in Fig. 19. This graph showcases the plotted values against time (minutes) and temperature (°C), following the ISO-834 [9] standard. The surface temperature and core temperature are plotted with respect to time (Fig. 20).

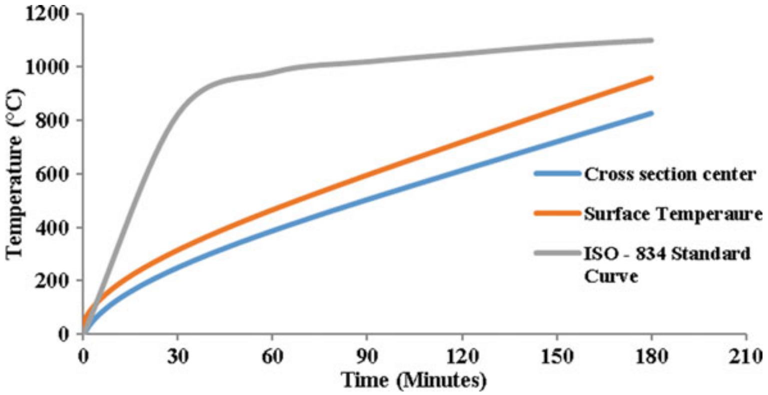

Fig. 19 Time vs. temperature curve as per ISO-834

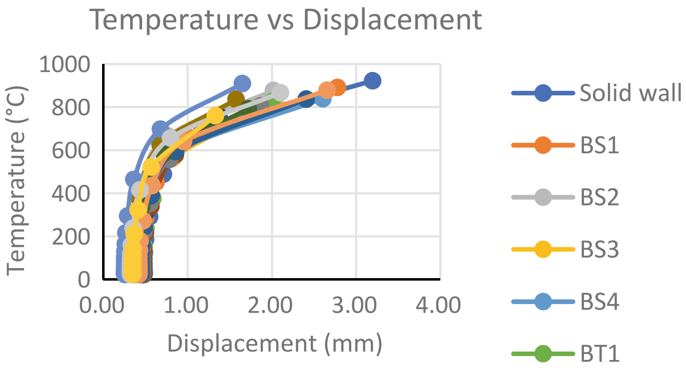

Fig. 20 Temperature vs. displacement graph

The temperature vs. displacement graph has been plotted based on the point at which the failure occurs, in order to understand the effect of the pressure and surface heat flux applied over the 3D-printed concrete walls (Fig. 21).

The temperature variance graph has been plotted to understand the behavior of various 3D-printed concrete walls with and without the openings when exposed to high temperatures (Fig. 22).

The displacement graph has been plotted to understand the displacement occurring on various 3D-printed concrete walls (Fig. 23).

The shear stress graph has been plotted to understand the shear stress occurring on various 3D-printed concrete walls (Fig. 24).

The time period graph has been plotted to understand the time required by various 3D-printed concrete walls with and without the openings to fail due to the pressure and surface heat flux applied over it.

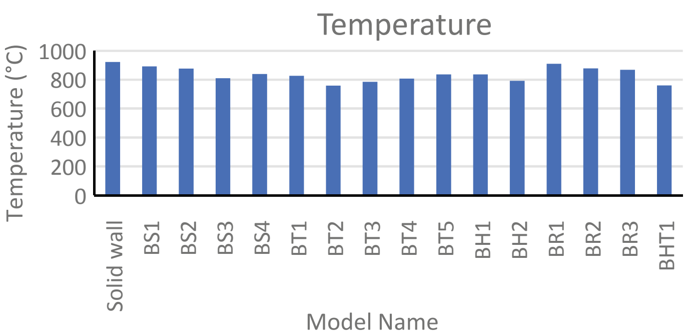

Fig. 21 Temperature variance graph

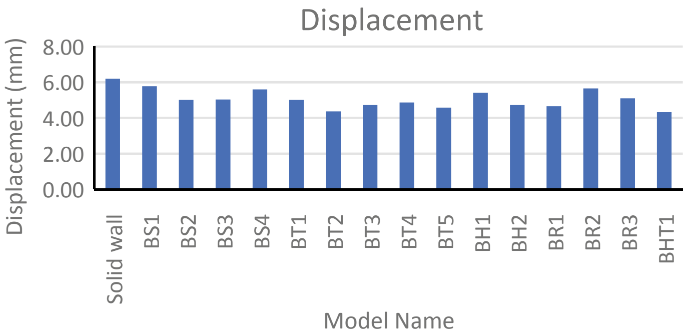

Fig. 22 Displacement graph

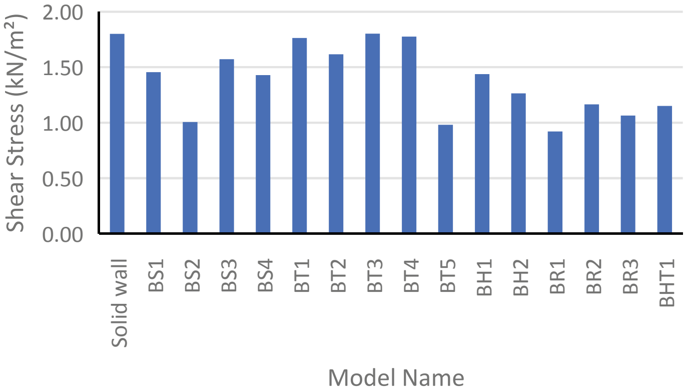

Fig. 23 Shear stress graph

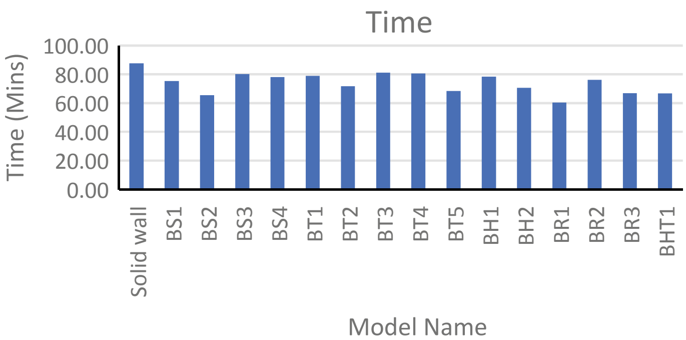

Fig. 24 Time period graph

5 Conclusion

With the results obtained from performing finite element research on the study of three-dimensionally printed concrete walls under high temperatures, a comprehensive analysis was conducted on 16 wall models, including variations with and without openings of different shapes. Based on these analyses, the following conclusions can be drawn:

- It can be observed that the maximum displacement of 6.20 mm was found in the 3DPC solid wall which has no openings. When the openings are provided in the wall, a maximum displacement of 5.78 mm can be observed in the BS1 wall which has been provided with five square-shaped openings.
- It can be observed that the minimum displacement of 4.33 mm was found in the BHT1 wall with 28 hexagonal and triangular openings.
- It can be observed that the 3DPC solid wall which has no openings can withstand the highest temperature of 922 °C when compared to the other walls. When the openings are provided in the wall, it can be observed in the BR1 with five rectangular openings which can withstand the highest temperature of 909 °C when compared to the other walls with openings.
- It can be observed that the BT2 wall with ten triangular openings withstands the lowest temperature of 759 °C when compared to the other walls with openings.
- It can be observed that the 3DPC solid wall displays the most shear stress of 1.80 N/mm^2 along with the BT3 wall with ten mini-triangular openings.
- It can be observed that the BR1 wall with five rectangular openings displays the lowest shear stress of 0.92 N/mm^2 when compared to the other walls.

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