Analysis of 3D printed concrete wall under cyclic loading

Dr. Roopa M[1], Harshitha P S[2]
[1]Assistant Professor, Department of Civil Engineering, Siddaganga Institute of Technology, Tumkur, Karnataka, India.
roopam@sit.ac.in
[2]MTech, Department of Civil Engineering, Siddaganga Institute of technology, Tumkur, Karnataka, India.
1si22cse06@sit.ac.in

Abstract

The use of 3D printed concrete (3DPC) in construction is gaining prominence due to its potential for enhanced customization, reduced waste, and rapid construction processes. However, the structural performance of 3DPC under dynamic conditions, such as seismic or cyclic loading, remains underexplored. This study focuses on the analysis of 3D printed concrete structures subjected to cyclic loading to evaluate their durability and mechanical behavior. Using finite element modeling (FEM) in Abaqus, the study simulates cyclic loading conditions to assess stress distribution, crack propagation, and energy dissipation in 3DPC. Experimental validation is conducted by comparing simulation results with data from physical tests. The findings offer insights into the performance of 3DPC under cyclic stress, which is critical for its application in earthquake-prone regions. This research contributes to developing design guidelines for 3D printed concrete structures in dynamic environments, enhancing their safety and resilience.

Keywords: *Cyclic loading, Seismic loading, Stress distribution, Crack propagation, Energy dissipation, Structural performance*

1. Introduction

3DPC: This new technology has encouraged and transformed the construction sector with more design freedom, lesser wastage of materials, and faster construction time. In comparison with other conventional construction techniques, this process eliminates all the traditionalism of formwork and can produce critical geometries at very fine tolerances, thus transforming the construction scenario [1][6][15]. This trend implies that gigantic infrastructural designs are well within expectation to get incorporated with 3DPC to a large extent at places where optimized and customized designs are to form the focal part of their endeavors [8][12]. Yet, despite much promise associated with 3DPC, its structural performance under dynamic loading conditions, such as the combined effects from seismic and cyclic loads, remains still behind in terms of developed scholarly research [2][5][11].

Indeed, cyclic loading itself presents a significant challenge since the fatigue and degradation in material properties are likely to occur after applying multiple loading cycles. As 3DPC materials involve intrinsic anisotropy through their layer-by-layer deposition processes, which might provoke weak interlayer adhesion, such materials are more susceptible to damage under cyclic stresses [3][7][10]. Many previous studies have indicated that the cyclic performance of 3DPC elements is highly dependent on the orientation of layers and the infill patterns and material composition, for example, in the studies conducted on stress distributions, crack propagation, and energy absorption

[4][9][13]. The aim of the current paper is to fill this knowledge gap by concentrating on the cyclic behavior of 3DPC. Particularly, this study focuses on the distribution of stresses and cracking patterns of and the energy consumption by the FEM approach by using Abaqus software [14][8]. Reliability would be established by proving the outcomes of FEM through experimental data. The comprehensive understanding of the performance of 3DPC in dynamic environments will be ensured [5][12]. These results shall go into design guidelines of 3DPC structures, especially seismic regions for ensuring safety and durability in their function [1][15].

Simulations under various cyclic loading scenarios shall be performed using advanced FEM techniques. Through these simulations, the behavior of 3DPC structures under various frequencies and amplitudes shall be evaluated. Dynamic Load Resistance in 3DPC Elements: Various material compositions and printing parameters would be analyzed in terms of cyclic performance so that avenues for improvement would be recognized. Additionally, the findings gathered from this research regarding the analysis of a dynamic geodesic dome structure [16] are envisaged to be used for more robust 3DPC design and further adoption in seismically active areas.

This research contributes not only to the fundamental understanding of 3DPC behavior under cyclic loading but also toward the pathway of future work in advanced material development and optimized designs. Such findings are relevant in the transition of the construction industry toward sustainable and resilient structures, with the contribution of this research likely to form a significant part of the next generation of construction technologies. This can lead to creating 3DPC-based infrastructure that is resilient, energy efficient, and structurally sound and potentially transformative.

2. Analytical model

This analytical model evaluates the structural performance of a 3D printed concrete wall with dimensions of 2 meters in length, 1 meter in height, and 0.2 meters in width.

The study aims to understand the stress distribution, deformation characteristics, and overall stability of the wall under different loading conditions using fundamental principles of structural mechanics. The wall is modelled as a rectangular solid, assuming homogeneous and isotropic material properties for the 3D printed concrete, The material properties were characterized using the Drucker-Prager model, which effectively simulates concrete-like materials under compression. Key material parameters included a density of 2.5×10^9 kg/m³, a friction angle of 36°, a flow stress ratio of 1, and a dilation angle of 11.3°. The Drucker-Prager hardening was defined with yield stresses of 10 MPa and 20 MPa at corresponding plastic strains of 0 and 12,000,000, indicating a strain hardening behavior when subjected to compressive loads.

The analysis aimed to capture the inelastic and plastic deformation behavior under cyclic loading, mimicking real-world earthquake loading scenarios. A displacement-controlled sinusoidal load was applied to observe energy dissipation, stiffness degradation, and progressive damage over multiple cycles. The findings offered valuable insights into the wall's crack initiation, propagation, and potential failure modes, emphasizing both the advantages and limitations of 3D printed walls in load-bearing applications under dynamic conditions. This study enhances the understanding of the structural integrity and resilience of 3D printed concrete structures when exposed to repeated loads.

A dynamic explicit analysis was set up with several steps to effectively simulate the load conditions. Two main steps were outlined as follows: Step-2: This step was defined with a duration of 10 seconds. Nonlinear geometry effects (NLGEOM) were disabled to eliminate large displacement effects that could influence the following steps. The option to include adiabatic heating effects was also turned off, as thermal effects were not the primary focus of this analysis. Pressure - Gravity Loading: A distinct step for gravity loading was established with a shorter duration of 1 second, also with NLGEOM turned off to maintain linear assumptions regarding displacement effects. Adiabatic heating was once again excluded to prevent complications related to thermal considerations. These configurations facilitated a controlled and simplified simulation of load effects while ensuring computational efficiency. By keeping NLGEOM off, the model assumes small deformations, allowing the simulations to proceed without the need to account for significant geometric nonlinearities, making it appropriate for the scope of the study.

The friction formulation was configured to Penalty, featuring isotropic directionality to guarantee consistent friction characteristics across all directions. The friction coefficient was set at 0.75. To keep the model straightforward, advanced options like slip-rate, contact-pressure, and temperature-dependent data were not enabled.

3. Methodology

3.1 Objective and Model Setup

An attempt has been made to analyze the cyclic behavior, failure modes, and energy dissipation of 3D printed concrete walls in the process of cyclic loading. The wall is modelled with specific dimensions and 3D printing characteristics with a refined hexahedral mesh in the high-stress regions.

3.2 Material Properties and Boundary Conditions

In this study, mechanical properties such as compressive strength and Young's modulus with orthotropic behavior were defined to the material 3DPC to provide an attribute that is inherent of the printed material. Concrete damage plasticity is used to simulate crack formation and cyclic degradation. Fixed supports at the base will reduce computational time with the help of symmetry.

3.3 Cyclic Loading and Interlayer Interaction

The cyclic sinusoidal or triangular load pattern simulates progressive loading to the model, and interlayer bonding is represented through properties of a cohesive model where friction on the bond interface represents the bond effect when the stiffness is under cyclic stress.

3.4 Simulation and Analysis

Analysis Uses nonlinear geometry settings for large deformations and adaptive meshing in areas that may potentially fail. A run is performed while monitoring convergence, and some of the data meant to be extracted are used for evaluation purposes: stress-strain, load-displacement curves, and energy dissipation.

3.5 Post-Processing and Validation

Damage and structural integrity are evaluated from crack patterns, stiffness degradation, and failure modes. Simulations are compared with experiments. Some of the key sensitivity parameters, for example interlayer strength and the load amplitude, are studied.

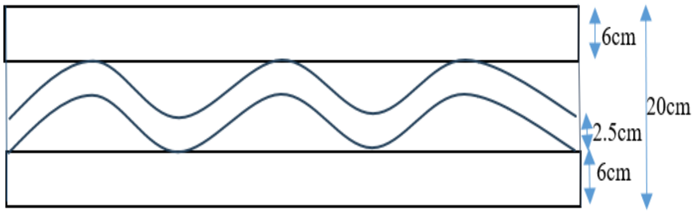

Figure 3.1. Lateral cross section of the wall

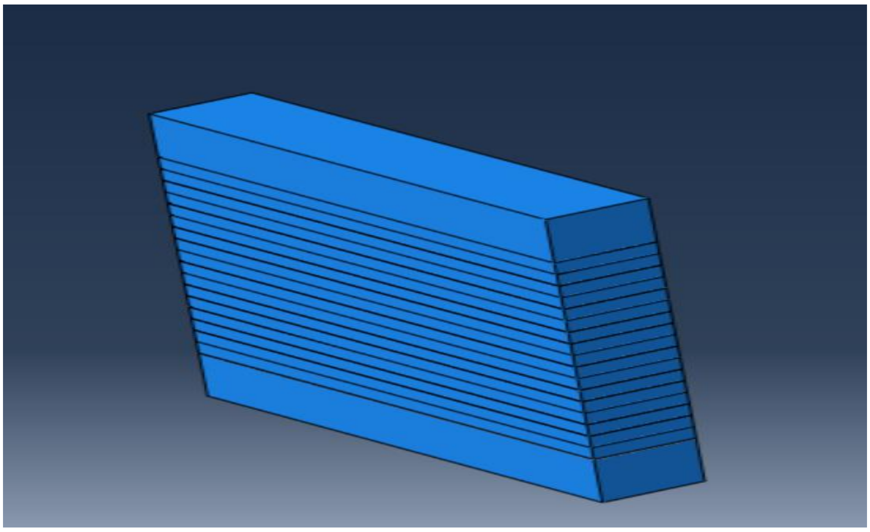

Figure 3.2. Analytical model of the wall

4. Results and Discussions

Table 1: Analysis result

Step	Increment	Total Time (s)	Step Time (s)	Stable Time Increment	Kinetic Energy	Total Energy
1	61	0.51	0.51	0.0092	0	0
1	336	3.04	3.04	0.0092	0	0
1	666	6.09	6.09	0.0092	0	0
1	1091	10	10	0.0092	0	0
2	7	10.05	0.05	0.0078	5.32E+07	-8528.3
2	39	10.31	0.31	0.0078	1.55E+09	-10002.4
2	66	10.55	0.55	0.0092	5.01E+09	-32356.7
2	99	10.86	0.86	0.0092	1.19E+10	-40105.2
2	115	11	1	0.0092	1.62E+10	-37239.7

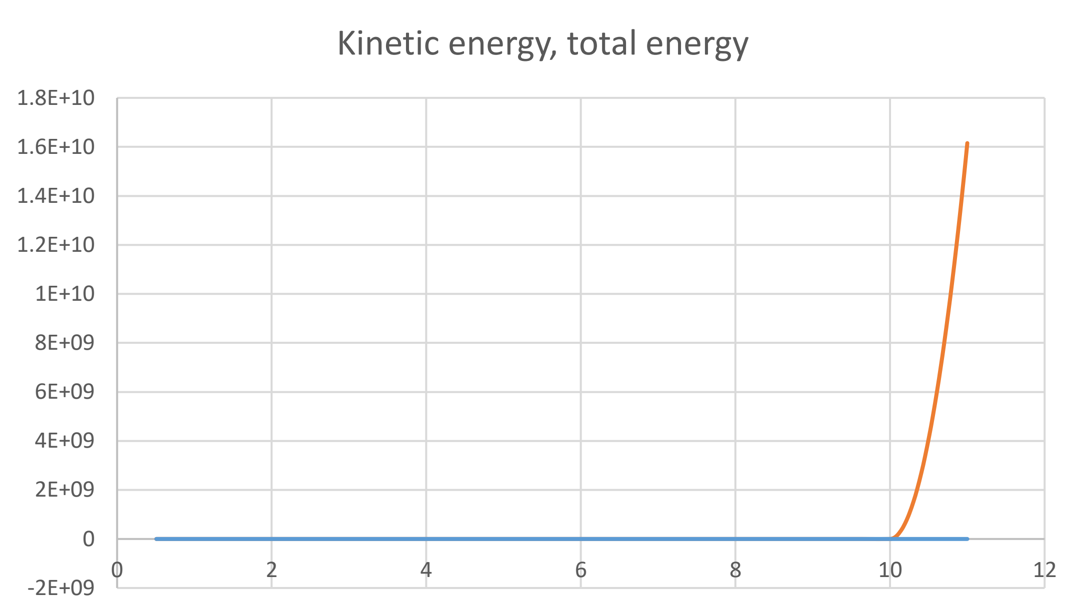

Figure 4.1. Time Vs Kinetic energy and Total energy

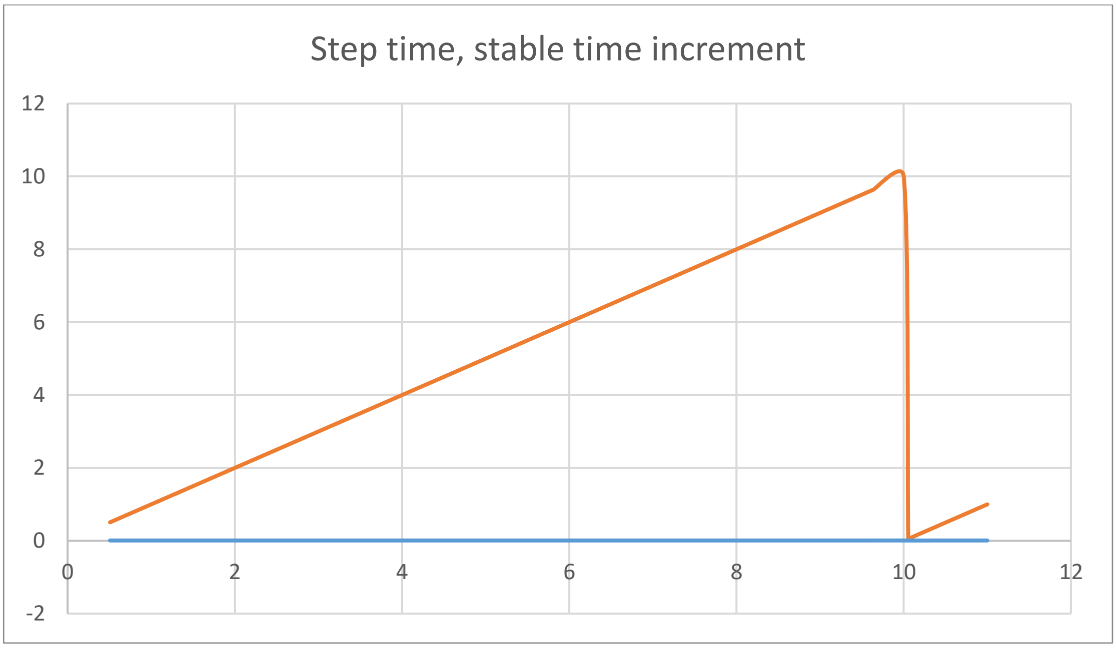

Figure 4.2. Time Vs Step time and Stable time increment

- **Time Elapsed and Simulation Stability:**
  The simulation consists of two steps, with two different increments within those steps. In step one, Total Time is incremented; by the last increment it has yielded about 10 seconds. In step two, Total Time is incremented on every increment.
  The Constant Step Size in Step 1 is 0.00921989 while decreases to a value of about 0.00784422 in Step 2. This reduction in value further indicates changes in the stability condition, perhaps because dynamic activity increases in Step 2, so the simulation sustains numerical stability under changing conditions.

- **Energy Dynamics :**
  Kinetic Energy is zero throughout Step 1. Presumably, the system is either in a steady or an initialization phase without active motion or forces applied. In Step 2, kinetic energy begins at 5.32×1 0 7, and then builds to about 1.61×1 0 10.
  by the end of the step. Such an increase in kinetic energy means that there must be motion or energy input into the system as a result of applied forces or a changed configuration.
  Total Energy is also zero at all points in Step 1, which coincides with the total effect on the kinetic energy. At step 2, total energy increases continuously and becomes more and more negative from -8528.3 up through -37239.7. The persistent decrease in total energy would signify an energy loss; this may be caused either by damping forces or friction forces or some other mechanisms associated with dissipation in the system.

- **Physical Interpretation:**
  The trend of increasing kinetic energy in Step 2 reads that motion enters after an initial stationary phase, as read in Step 1. In the physical scenario, this could easily present a scenario whereby the system is initially at rest and then subjected to external forces, which could ultimately lead to dynamic motion.
  The total energy decreases linearly as it becomes more negative. Probably it is because of dissipative forces (damping or friction) at work. This is a typical behavior in systems where the energy is applied initially but otherwise dissipated through resistances-internal or external-driving the system toward a lower energy state or equilibrium.

- **Simulation Behaviour**
  This means that the change in Step 2 of the Stable Time Increment of the simulation changes its stability parameters in adjusting to more dynamic activity. It is a very important kind of adjustment so that even when energy changes dramatically over time, the stability of the calculations remains the same.

- **Implications and Applications**
  This kind of simulation is helpful especially in structural engineering, materials science, and physics, where energy transfer and dissipation must be clearly understood. In that context, structural testing or fatigue analysis of a system that begins from a stable state but then undergoes additional energy input in the form of a load or force is a common application. The fact that this total energy dissipated would indicate material stability or failure points can also give an overview of a system's efficiency.
  Summary In summary, this artificial data demonstrates that starting from an initial resting state (Step 1), the system will proceed to active motion with energy injection and dissipation (Step 2). As kinetic energy increases while total energy decreases, that there is both the introduction of motion and dissipative forces that push the system toward equilibrium. From the stability parameters changes, it shows this simulation is very robust, capable of dealing with variations in conditions, and is a good approach toward understanding energy behaviors in dynamic systems.

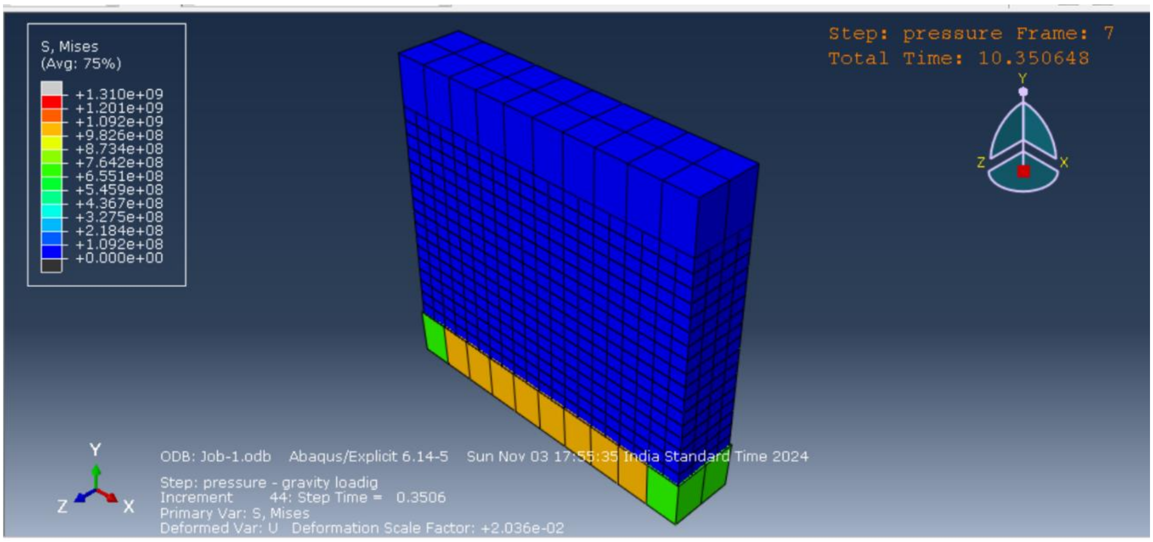

Figure 4.3. Deformation

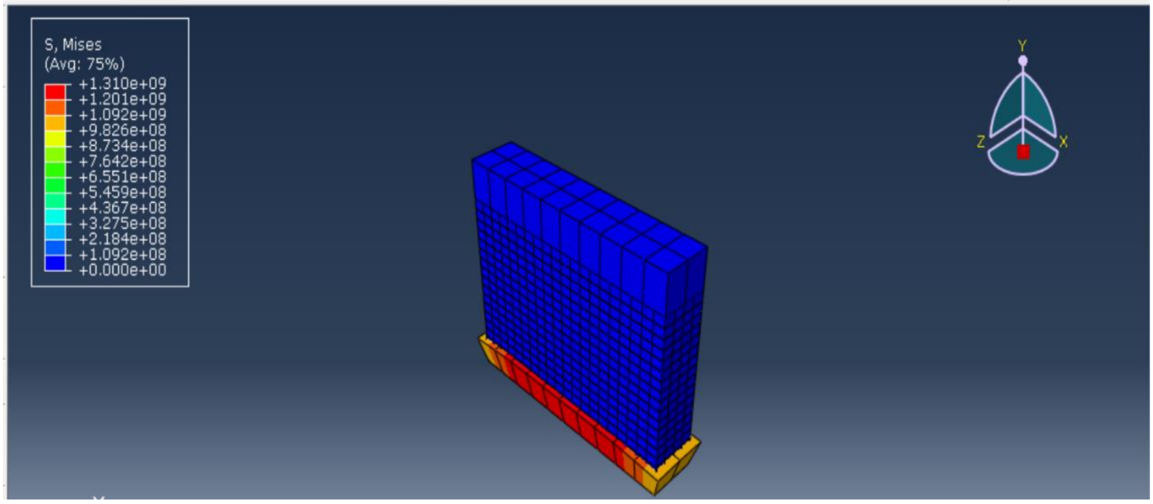

Figure 4.4. Failure mode

5. Conclusion

- Energy Surge at Failure Threshold: Figure and Discussion of Kinetic and Total Energy Plot Kinetic and total energy plot The plot presents a high peak close to the time of 10 units for the kinetic and total energy corresponding to a turning point in the loading cycle. This increase corresponds to the point where the wall can no longer dissipate energy effectively, marking the onset of a possible structural failure. It represents an instantaneous energy release due to the fact that the absorbed energy level of the material is surpassed, potentially leading to a loss of stability and structural failure.

- Time Increment Stability: The stable time increment compared with the time step revealed that with consistent increases to around 10 units, a sharp drop is shown. Such a drop aligns with the peak energy increase and therefore denotes a loss in numerical stability because the model is approaching failure. At this stage, a need for smaller increments heightens the challenge of maintaining simulation stability, similar to the inability of the wall to have cyclic loading increases.

- Stress Concentration and Failure Zones: A stress concentration is seen at the base of the wall with a maximum of 1.31 × 10^9 Pa in the von Mises stress distribution map. The zones of high stress indicate that the base is the weakest point when cyclic loading is applied, consistent with intuitive expectation for a fixed base structure. The stress gradient which decreases from bottom up is validated in order to be certain that the major element of the reinforcement needed is actually at the bottom of the wall.

- To summarize: Based on the collective result, it can be said that 3D printed walls loaded under cyclic loading experience a certain failure threshold; characterized by sharp rise in energy, instability in increment of time, and a high concentration of stresses at the bottom. This means that while the base reinforcement is important, improvement should also be placed on the core reinforcement for the structural resilience. One avenue that could improve the performance and safety of the 3D printed walls under real loading conditions may be promising further development for the optimized material formulations and targeted reinforcement.

Acknowledgments

I would like to extend my heartfelt thanks to my advisor, [Dr. Roopa M], and my institution, Siddaganga institute of Technology, Tumkur, for the guidance and support received in conducting this research on 3D printed concrete walls under cyclic loading. I am thankful to my family and friends for encouragement and their constant support.

References

[1] K. A. S. G. Harsh, P. C. P. Wu, and J. L. B. B. De Jong, "Mechanical Properties of 3D Printed Concrete: A Review," Materials, vol. 13, no. 4, (2020), pp. 1022.

[2] T. D. A. Van Zijl, C. S. J. R. Van Gils, and H. J. P. P. Van der Meer, "Cyclic Loading of 3D Printed Concrete Structures: An Experimental Study," Journal of Structural Engineering, vol. 146, no. 7, (2020), pp. 04020113.

[3] J. M. R. de Andrade, R. F. S. N. de Oliveira, and E. G. J. L. Alves, "Cyclic Behavior of 3D Printed Concrete: Implications for Structural Design," Construction and Building Materials, vol. 220, (2019), pp. 882-895.

[4] A. P. J. R. de Silva, M. M. C. H. de Alencar, and E. M. R. P. C. Baptista, "Investigating the Durability of 3D Printed Concrete Under Cyclic Loading," Materials Science for Energy Technologies, vol. 1, no. 1, (2018), pp. 103-110.

[5] M. S. M. G. Abid, M. R. H. Y. B. Alawad, and M. J. K. K. N. M. Alam, "Performance of 3D Printed Concrete Under Repeated Loading: Insights and Challenges," Journal of Cleaner Production, vol. 230, (2019), pp. 135-146.

[6] Z. N. Malaeb, H. K. Ayoub, and J. A. Maalouf, "3D Concrete Printing: Machine and Mix Design Optimization for Strength and Cost," Automation in Construction, vol. 61, (2016), pp. 1-11.

[7] S. Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, "Cyclic Loading Behavior of 3D Printed Concrete: Experimental and Numerical Investigation," Cement and Concrete Composites, vol. 104, (2019), pp. 103367.

[8] B. Panda, L. N. Tay, and M. J. Tan, "Correlation Between Print Layer Orientation and Mechanical Properties of 3D Printed Concrete Under Cyclic Loading," Materials Letters, vol. 245, (2019), pp. 180-183.

[9] R. J. Bos, R. Wolfs, Z. Ahmed, and T. Salet, "Structural Integrity of 3D Printed Concrete Walls: A Cyclic Load Study," Engineering Structures, vol. 200, (2019), pp. 109-119.

[10] M. Zhang, Z. Wang, and Q. He, "Performance of 3D Printed Concrete Subjected to Cyclic Loading and its Implications for Structural Design," Journal of Materials in Civil Engineering, vol. 31, no. 11, (2019), pp. 04019284.

[11] J. Wolfs, F. Bos, and T. Salet, "Early Age Mechanical Response of 3D Printed Concrete under Cyclic Loading," Cement and Concrete Research, vol. 106, (2018), pp. 103-116.

[12] T. A. Buswell, W. R. Leal de Silva, and R. J. Lark, "Evaluation of 3D Printed Concrete Layers under Fatigue and Cyclic Loading," Procedia Engineering, vol. 172, (2017), pp. 29-36.

[13] H. Lim, A. Buswell, R. Leal, and W. Zhu, "Mechanical Performance of Interlayer Adhesion in 3D Printed Concrete Under Cyclic Loading," Materials Science and Engineering: A, vol. 811, (2021), pp. 141069.

[14] G. Ma, B. Li, and H. Wang, "Influence of Infill Pattern and Layer Orientation on Fatigue Life of 3D Printed Concrete Elements," Construction and Building Materials, vol. 239, (2020), pp. 117829.

[15] S. R. Smith, M. J. Tan, and B. J. Kazemian, "Durability and Load-Bearing Capacity of 3D Printed Concrete Walls Under Repeated Loading," Additive Manufacturing, vol. 33, (2020), pp. 101118.

[16] M. Roopa, Kavitha B. Lakshmi, and H. Venugopal, "Dynamic Analysis of Geodesic Dome Structure," Conference Paper, First Online: 03 September 2021, pp. 895–915.