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NUMERICAL EVALUATION OF THE SEISMIC PERFORMANCE OF SELF-CENTERING 3D PRINTED CONCRETE WALL

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Abstract

3D concrete printing is an innovative additive manufacturing technique that holds significant promise for large-scale structural applications. However, to ensure its effectiveness under complex loading conditions, such as cyclic loading, the incorporation of reinforcement is essential. A key challenge lies in integrating reinforcement into 3D printed concrete (3DPC), as the reinforcement must be compatible with the layer-by-layer construction process inherent to this technology. In this study, we addressed this challenge by implementing a centered reinforcement strategy and modelled a self-centering 3DPC wall. The primary objective is to evaluate the structural behavior of self-centering 3DPC wall under cyclic loading. To accurately replicate the behavior of 3DPC wall, material characterization and 3D finite element dynamic analysis (FEA) are established, incorporating detailed experimental input parameters such as stiffness coefficients and interlayer bonding properties. These parameters are crucial for achieving a realistic simulation of the wall's performance. A simplified micro-modelling approach is employed to analyze the load-bearing behavior of 3DPC walls under quasi-static cyclic in-plane loading conditions. The results demonstrated that the implemented reinforcement strategy significantly enhanced the cyclic performance of the 3DPC wall by 54.08%, improving wall's stability and damage tolerance. After parametric investigation, computational findings suggest that the seismic performance of the 3DPC wall considerably enhanced by combining a solid 3DPC wall with a 32 mm central reinforcement bar with the ultimate load capacity increasing by 65.79% compared to the self-centering 3DPC wall. The study provides critical insights into the seismic performance of reinforced 3DPC structures, underscore the potential of optimized reinforcement strategies in enhancing load resistance of 3DPC walls, delaying structural deterioration, and improving overall resilience—key considerations for seismic applications.

Keywords: 3D Concrete Printing, Self-Centering Systems, Cyclic Loading, Seismic Resistance, Finite Element Anlysis.

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1 INTRODUCTION

In recent years, 3D printed concrete (3DPC) has emerged as a transformative technology, offering unparalleled design flexibility, material efficiency, and automation-driven construction advantages [1]. The rapid advancements in extrusion-based 3DPC have enabled its practical application, challenging conventional construction techniques by reducing labor demands and allowing for complex architectural geometries. However, despite these technological strides, the structural design of 3DPC elements remains in its early stages of development [2], particularly regarding reinforcement integration, which is a critical factor in ensuring structural integrity and performance under extreme loading conditions such as earthquakes. Unlike traditional construction methods such as masonry or precast concrete systems, where reinforcement strategies are well-established, the direct incorporation of reinforcement within 3DPC structures presents significant engineering challenges due to limitations in printability, bond performance, and continuity [3-5].

As 3DPC technology expands into load-bearing [6-8] and earthquake-resistant applications [9-12], it becomes imperative to establish reinforcement solutions that are both practical and structurally effective. One such approach is the integration of self-centering reinforcement systems, which offer ease of implementation within the printing process while simultaneously enhancing the seismic resilience of 3DPC walls. A self-centering reinforcement strategy can provide enhanced lateral stability and improved energy dissipation, due to its reduced residual deformations, making it a viable solution for large-scale adoption in earthquake-prone regions. However, the current understanding of 3DPC wall behavior under cyclic loading remains limited, necessitating detailed investigations into its failure mechanisms and response characteristics. Existing literature often assumes that the structural behavior of 3DPC walls is analogous to that of masonry or precast walls. However, this assumption is not well-justified, as key parameters such as tensile cracking resistance, dowel action in vertical reinforcement, and shear/flexural interaction behave differently in 3DPC due to its unique layered deposition process, interlayer bond characteristics, and anisotropic material properties [13]. Consequently, traditional modeling approaches may fail to accurately predict load distribution, crack propagation, and failure patterns in 3DPC walls. A comprehensive assessment of these structural characteristics is essential to establish design guidelines for earthquake-resistant 3DPC walls.

To bridge these research gaps, this study investigates the seismic performance of 3D-printed walls with integrated self-centering reinforcement (3DPC-SC) using a numerical micro-modeling approach, as detailed in [12]. The adopted model accurately captures layer interfaces and reinforcement mechanisms, enabling a detailed assessment of self-centering behavior under cyclic loading. A parametric study is further conducted to evaluate the influence of key design parameters, including the effect of solid 3DPC wall, reinforcement bar diameter, and the combined impact of both, on the overall seismic response of 3DPC walls. The results indicate that the self-centering 3DPC wall effectively mitigates unstable rocking behavior and prevents crushing failures while demonstrating controlled stiffness degradation and reduced residual deformations under quasi-static cyclic loading. The final section of this study highlights the effectiveness of the combined reinforcement strategy—integrating a solid 3DPC wall with a larger-diameter reinforcement bar—to enhance structural resilience under seismic loading. The computational findings reveal that the incorporation of a 32 mm central reinforcement bar in solid 3DPC wall significantly improves seismic performance, increasing the ultimate load capacity by 65.79% compared to the self-centering hollow 3DPC wall with a 16 mm bar. These findings provide a strong foundation for the broader adoption of self-centering reinforcement strategies in 3DPC structures, reinforcing their resilience and practical feasibility in earthquake-resistant applications.

2 NUMERICAL MODELLING APPROACH

Here the widely used constitutive concrete damage plasticity (CDP) model was employed to address material nonlinearity, encompassing both tensile and compressive failures [11,12]. CDP was applied to both cast (top and bottom beam) and printed concrete (layers). Additionally, a comprehensive micro-model was utilized to define the layer interfaces of 3DPC, accurately capturing fundamental failure mechanisms that define the holistic structural behavior of 3DPC [12]. This micro-model facilitates capturing linear and fracture behavior of interfaces, based on traction-separation behavior between printed layers. The adopted cohesive model depends on a key parameter, i.e., the stiffness coefficient, which can be calculated via experimentation to give as input in numerical model [11].

2.1 Description of the 3DPC wall specimen and numerical model

In 3D finite element composite interface model, both the linear and non-linear behavior of the printed layers and interfaces are explicitly defined. Specifically, 3D hexahedral-shaped eight-node linear brick elements with reduced integration and hourglass control (type C3D8R) are employed to model the printed layers, top and bottom beam.

For the interfaces between printed layers, a surface-to-surface cohesive discretization approach is applied, utilizing finite sliding formulation. Whereas a surface-to-surface interaction is established to facilitate communication between the bottom and top layer of wall with bottom and top cast beam connected to the 3DPC lattice wall. For further information on cohesive discretization and the selected mesh size of 50 mm, see [12].

Encastre boundary condition was used to replicate the fixed-base conditions and loads on 3DPC lattice walls are applied in two steps (Figure 1a): initially a pre-compression vertical stress of 0.5 MPa is applied which was kept constant during the test, and then the walls are subjected to horizontal in-plane cyclic loads under displacement control. The wall considered for this study is subjected to 21 number of cycles [1] (Figure 1b). The cyclic load applied to the control node and the pre-compression on the top surface of the top beam, respectively. All specimens underwent displacement-controlled cycle mode with 1 mm increment. A non-linear dynamic implicit procedure is followed in this study, thus facilitating the pursuit of a quasi-static solution that iteratively resolves equilibrium at each increment.

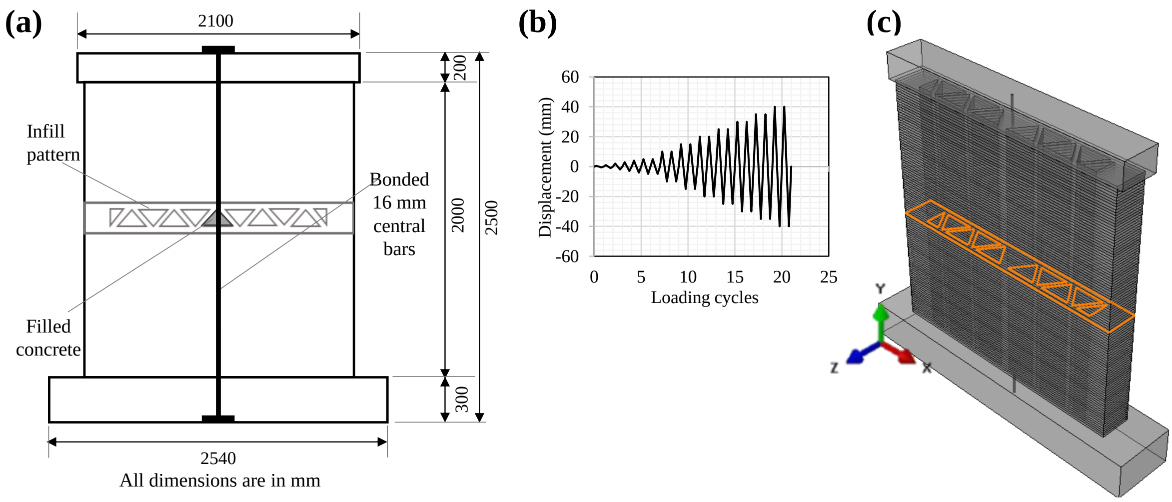

Figure 1: (a) Section detailing with infill pattern; (b) cyclic loading protocol; (c) elevation of the 3DPC wall.

2.2 Material properties for modelling

The material properties of 3DPC were obtained from the testing of printed cubes of size 50 mm × 50 mm under uniaxial compression and split tensile. The compressive and split tensile strength were measured using a constant displacement control rate of 1 mm/min [14]. The comprehensive stress-strain response of 3DPC under compression and tension, and reinforcements are given in Table 1. All other parameters are detailed in Table 1, serves as input in ABAQUS FEM package to accurately capture the behaviour of 3DPC wall reinforced with centered reinforcement, as shown in Figure 1c.

Interface-based model		Concrete Damage Plasticity model	
Young modulus of 3DPC, E_c (N/mm^2)	24584	Ultimate compressive and tensile stress of 3DPC, f_{cm}, f_{ctm} (N/mm^2)	7.35, 3.27
Poisson ratio, v	0.2 [15]	Strain at peak stress, ε_{c1}	0.0022
Shear modulus of 3DPC, G_c (N/mm^2) (Calculated by $E=2G(1+v)$)	10243.33	k	2.32
layer thickness, t_c (mm) as per assumption	15	Compressive yield stress of 3DPC, σ_{co} (0.4 f_{cm}) (N/mm^2)	14.4
Normal interface elastic stiffness, K_n (N/mm^3)	1639	Density (N/mm^3)	21000
Tangential interface elastic stiffr $K_s = K_t$ (N/mm^3)	683, 683	Dilation Angle (degree)	35^0
Specific fracture toughness for Mode I, G_{IC} (N/mm)	0.29 [12]	Flow potential eccentricity	0.1
Specific fracture toughness for Mode II and III, G_{IIC}, G_{IIIC} (N/mm)	0.6, 0.6 [12]	Ratio of biaxial compressive yield stress to uniaxial compressive yield stress (f_{b0}/f_{c0})	1.16
Friction coefficient	0.75 [16]	Ratio between second stress invarient on the tensile meridian and that on the compressive meridian, K	0.67
		Viscosity parameter	0.00001 [12]

Table 1: Input parameters used for the numerial simulation.

3 RESULTS AND DISCUSSION

The results of this study demonstrate that the reinforcement plays a crucial role in enhancing the seismic performance of 3DPC walls. The increased redundancy provided by the central reinforcement enhances the wall's resilience to seismic forces by improving its ability to resist localized failures and resist toe crushing with a stable rocking failure, particularly in areas of high stress concentrations such as near openings or wall boundaries.

3.1 Seismic performance analysis

The numerical simulation results of the 3DPC and 3DPC-SC systems are presented in Figure 2, illustrating the crack propagation patterns, failure mechanisms, and structural enhancement achieved through self-centering reinforcement under cyclic loading. As the applied displacement increased, the unreinforced 3DPC wall exhibited extensive horizontal and vertical cracking, ultimately leading to wall toppling and concrete crushing, as shown in Figure 2b.

In contrast, the 3DPC-SC wall demonstrated a more controlled crack evolution. Initial cracking originated near the centrally positioned reinforcement bar and extended diagonally downward but did not propagate toward the toe and heel regions. This behavior can be attributed to the confining effect provided by the reinforcement, which effectively restricted crack propagation within the central region (Figure 2b).

The self-centering reinforcement strategy significantly improved the lateral load capacity, with the 3DPC-SC wall achieving a peak load of 238 kN at a displacement of 9.19 mm (Figure 2a), representing a 54.08% enhancement compared to the unreinforced 3DPC wall. In the post-peak phase, substantial concrete damage was observed in the lower regions of the 3DPC-SC wall, particularly between the reinforcement bars and the edge column (Figure 2c). This damage primarily resulted from localized stress concentrations and material degradation at the transition zone between reinforced and unreinforced regions, where shear and flexural stresses peaked, leading to crack widening and eventual concrete crushing. The findings underscore the critical role of strategically positioned reinforcement in enhancing the structural integrity and failure resistance of 3DPC walls under cyclic loading.

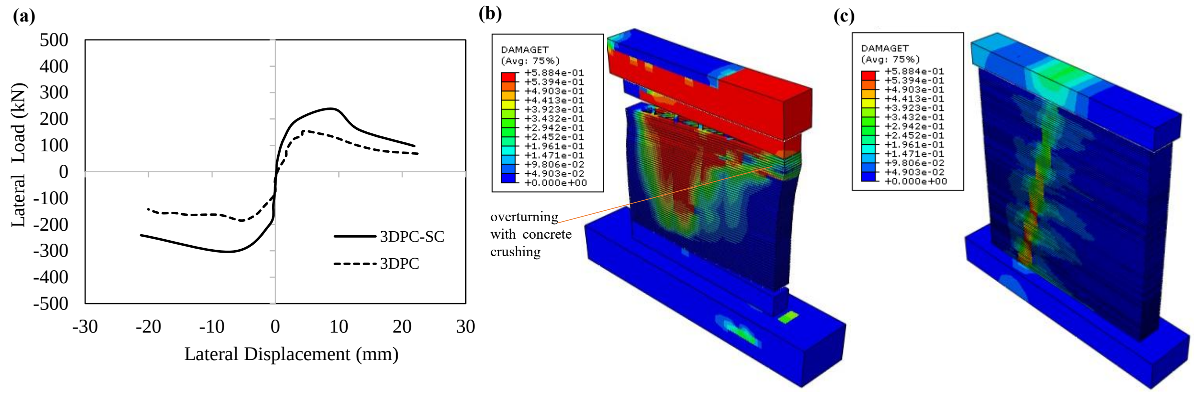

Figure 2: Numerical results (a) backbone curves of the hysteretic response; numerical failure mode of (b) 3DPC; (c) 3DPC-SC.

3.2 Parametric analysis of numerical results

A parametric study is conducted to evaluate the sensitivity of the 3DPC-SC wall by systematically varying key design parameters, including the solid 3DPC wall configuration, reinforcement bar area, and the combined effect of the best-performing reinforcement bar with the solid 3DPC wall. A total of six additional 3DPC walls are analyzed to assess these variations. The material properties detailed in Table 1 serve as the baseline model, while both geometric and material parameters are systematically modulated to quantify their influence on seismic performance. The findings from this parametric investigation are presented in the subsequent sections.

Effect of solid infill on 3DPC wall:

Figure 3 illustrates the envelope curve of the solid infilled 3DPC-SC, designed to investigate its influence on the cyclic in-plane load-bearing capacity of the wall. As expected, the inclusion of a solid infill enhances the structural integrity, leading to a notable improvement in load resistance. Specifically, the in-plane load capacity exhibits a 37.62% increase compared to the 3DPC-SC with a hollow infill pattern (Figure 1a). This enhancement is attributed to the increased confinement and load transfer efficiency provided by the solid infill, which mitigates localized stress concentrations and delays premature failure. Furthermore, a marginal increase in wall stiffness is observed, indicating improved resistance to lateral deformations under cyclic loading.

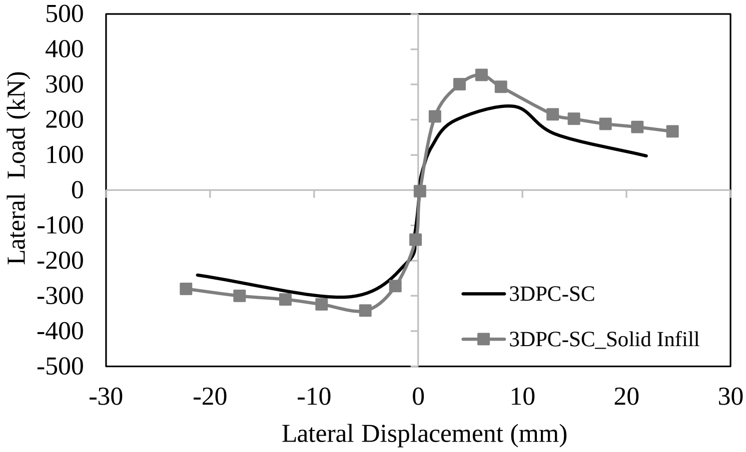

Figure 3: Effect of solid infill on cyclic in-plane loading capacity of 3DPC wall.

Effect of central bar diameter:

As part of the parametric study, the influence of central bar diameter on the cyclic loading capacity of the wall is anlysed and depicted through Figure 4. In the referenced self-centered wall (3DPC-SC), a 16 mm diameter reinforcement bar is used, whereas in this investigation, the diameter varies from 16 mm to 32 mm (i.e., 20 mm, 25 mm, 28 mm, and 32 mm). The selected bar diameters are based on standard reinforcement sizes available in the market, ensuring practical feasibility for real-world construction applications. The results indicate a progressive enhancement in the in-plane load capacity, with increments of 13.73%, 30.85%, 37.39%, and 49.81%, respectively. This improvement is attributed to the higher axial load-carrying capacity and improved bond characteristics of larger-diameter bars, which enhance energy dissipation and delay yielding.

Furthermore, an additional effect is observed in the softening regime of the load-displacement curve. As the bar diameter increases, the softening slope decreases, indicating a more stable post-peak response. The softening phase transitions into an almost straight response, signifying increased residual strength and delayed degradation in load resistance compared to the 16 mm bar.

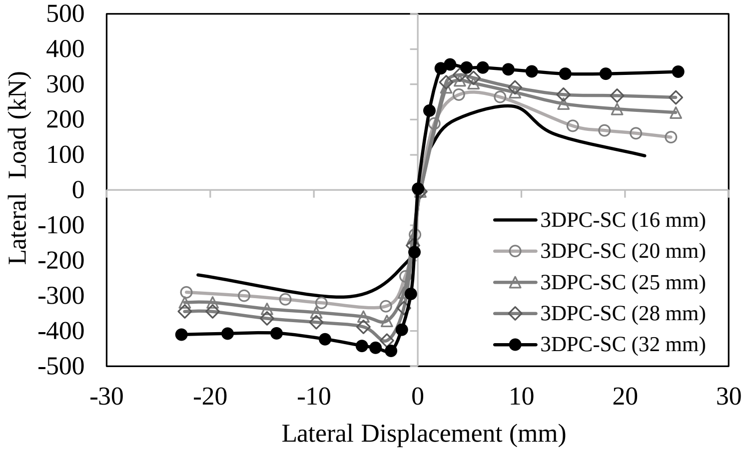

Figure 4: Effect of central bar diameter on cyclic in-plane loading capacity of 3DPC wall.

Combined effect of solid infilled 3DPC wall with 32 mm central bar:

Figure 5 illustrates the influence of combining 32 mm central reinforcement bar in solid 3DPC wall on the cyclic loading capacity of the wall. This configuration results in a substantial performance enhancement, with the ultimate load capacity increasing by 65.79% compared to the hollow 3DPC-SC reinforced with a 16 mm bar. The observed improvement highlights the dual role of the solid 3DPC wall in restricting lateral deformations and the larger-diameter reinforcement in augmenting axial force distribution and energy dissipation.

Furthermore, a notable shift in post-peak behavior is evident, highlighting the combined effect of the solid 3DPC wall and the 32 mm central reinforcement bar. Beyond a displacement of 15 mm, the load-bearing capacity exhibits a secondary increase, demonstrating enhanced strain-hardening characteristics and greater resistance to degradation. This substantial improvement is attributed to the synergy between the solid 3DPC wall and the optimized reinforcement, where the solid infill provides enhanced lateral confinement, mitigating premature cracking, while the larger-diameter bar ensures superior load redistribution and energy dissipation. The combined effect not only increases the peak strength but also extends structural stability under cyclic loading. This response is particularly advantageous for seismic applications, where sustained load resistance, delayed deterioration, and improved overall resilience are critical for structural performance.

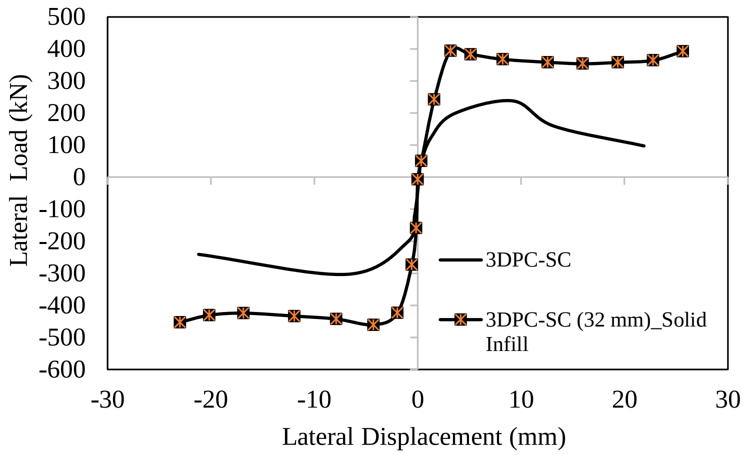

Figure 5: Combined effect of solid infilled 3DPC wall with 32 mm central bar on cyclic in-plane loading capacity of 3DPC wall.

4 CONCLUSIONS

The study highlights the enhanced seismic performance of 3DPC walls reinforced with a self-centering mechanism. the results demonstrate significant improvements in cyclic stability, load-bearing capacity, and damage control. The key contributions of this research include:

- **Effectiveness of self-centering reinforcement:** The incorporation of a centrally positioned reinforcement bar significantly enhanced the cyclic performance of the 3DPC wall, improving its lateral load capacity by 54.08% compared to the unreinforced 3DPC wall.
- **Controlled crack propagation:** In the 3DPC-SC system, cracks initiated near the reinforcement bar and remained confined within the central region, preventing extensive damage to the toe and heel areas, unlike the unreinforced wall, which exhibited widespread cracking and eventual toppling.
- **Failure mechanism and damage distribution:** The post-peak phase of 3DPC-SC exhibited localized damage primarily in the lower wall regions between the reinforcement bars

and edge column due to stress concentration and material degradation at the transition zone.

- **Combined reinforcement strategy:** The integration of a 32 mm central reinforcement bar with solid 3DPC wall led to a substantial 65.79% increase in ultimate load capacity compared to the hollow self-centering 3DPC wall with a 16 mm bar, demonstrating enhanced strain-hardening behavior and improved structural stability under cyclic loading.
- **Seismic resilience:** The findings establish that self-centering reinforcement, particularly when combined with a solid 3DPC wall, is an effective strategy for improving seismic performance, ensuring greater resistance to cyclic degradation and prolonged structural integrity.

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