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NONLINEAR FINITE ELEMENT INVESTIGATION OF 3D-PRINTED CONCRETE WALL PANELS UNDER DIAGONAL COMPRESSION

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ABSTRACT

This study investigates the in-plane behavior and damage mechanisms of three-dimensional (3D) printed concrete wall panels with dimensions of 600×600×150 mm using nonlinear finite element analysis. A three-dimensional finite element model of the wall panel was developed in ABAQUS. C3D8R solid elements with an approximate element size of 10 mm were employed in the model. The nonlinear behavior of concrete was simulated using the Concrete Damage Plasticity (CDP) model, which accounts for tensile cracking, compressive crushing, stiffness degradation, and plastic deformation. The specimen geometry, arrangement of the printed layers, interlayer interface behavior, boundary conditions, and diagonal loading configuration were incorporated into the finite element model. The interaction between the printed concrete layers was modeled using tie constraints defined between the surfaces of adjacent layers. Diagonal loading was applied under displacement control through the corner region of the wall panel. The load-carrying capacity and damage distributions obtained from the numerical analyses were compared with the results of an experimental study available in the literature. In addition, crack initiation regions, crack propagation paths, and critical damage zones were evaluated based on the damage distributions obtained from the numerical analysis. The finite element model successfully reproduced the experimental ultimate load-carrying capacity and the characteristic damage mechanism observed in the wall panel. Based on the experimental results, the relative error in the ultimate load-carrying capacity predicted by the numerical model was 5.75%. The findings demonstrate that the developed finite element model provides a reliable approach for the numerical assessment of the nonlinear in-plane behavior and damage evolution of 3D-printed concrete wall panels under diagonal loading. Furthermore, the present study may provide a basis for future numerical investigations in which interlayer interface behavior is examined in deep detail.

Keywords: 3D printed concrete wall panel, finite element method, Concrete Damage Plasticity (CDP), diagonal compression test.

1. INTRODUCTION

Three-dimensional concrete printing (3DCP) is an additive manufacturing method in which cement-based material is deposited layer by layer according to a digital model. The technology offers several advantages, including a substantial reduction in formwork requirements, lower labor demand and material waste, and shorter construction times It also provides greater design flexibility by allowing complex geometries that are difficult to produce with conventional construction methods and by enabling material to be placed only where needed. However, the broader, more reliable use of 3DCP in full-scale structural applications requires a clear understanding of the behavior of printed elements under various loading conditions.

The mechanical response of 3D-printed concrete may differ from that of conventionally cast concrete due to the layer-by-layer nature of the printing process. Weak bonding between successive layers, voids, and geometric irregularities introduced during printing can result in direction-dependent material behavior. Mader et al. (2023) showed that this directional dependency influences the nonlinear mechanical response of hardened 3DCP elements and can be represented using damage-plasticity-based models. An et al. (2024) reported that finite element predictions are influenced not only by the selected material model but also by boundary conditions, initial imperfections, and interactions between adjacent layers. The authors further noted that, with appropriate parameter selection, the Mohr–Coulomb and Concrete Damage Plasticity models can be used to predict the mechanical response and failure modes of 3DCP elements.

Three-dimensional printed concrete walls are among the main structural elements used to carry vertical loads in printed building systems. Their response to in-plane lateral loads is also important, particularly under seismic actions. Most previous studies have focused on compressive strength, flexural behavior, printability, and interlayer bond strength. In contrast, the in-plane shear response and crack development of printed walls have received comparatively less attention. Zhang et al. (2023) showed that the seismic performance of 3DCP walls is influenced by several factors, including layer interfaces, wall geometry, slenderness ratio, and reinforcement method. Liu et al. (2025) found that defects at the layer interfaces can significantly affect crack initiation and propagation. Their results also showed that X-shaped cracking and shear-compression failure may occur in 3D-printed reinforced concrete walls. These findings highlight the need to investigate the in-plane behavior of 3DCP walls not only through experimental studies but also using reliable numerical models. The diagonal tension test is widely used to evaluate the in-plane shear behavior of masonry walls. In this test, a square or nearly square wall specimen is subjected to compression along two opposite corners. This loading arrangement produces principal tensile stresses in the central region of the specimen. As the applied load increases, a diagonal crack generally develops in a direction approximately perpendicular to the loading axis. In this way, diagonal tension or shear cracking commonly observed in walls under seismic loading can be reproduced

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under laboratory conditions. The measured load and deformation data can then be used to evaluate key response parameters, including shear strength, deformation capacity, stiffness, and energy dissipation.

Although the diagonal tension test was originally developed for conventional masonry walls made of brick, block, or stone units, the layered structure of 3DCP walls presents certain similarities to these systems. In masonry walls, mortar joints may act as potential planes of weakness. Similarly, the interfaces between successive filaments in 3DCP elements can play a comparable role. When the interlayer bond is relatively weak, these interfaces may influence both load transfer and the path of crack propagation. For this reason, applying the diagonal tension test to 3DCP walls provides a useful approach for evaluating their in-plane shear performance.

Mercimek et al. (2026) investigated 3DCP wall specimens measuring 600 × 600 × 150 mm under monotonic and cyclic diagonal loading in accordance with ASTM E519. A distinct diagonal crack developed in the monotonically loaded specimen, whereas the cyclically loaded specimen exhibited more distributed microcracking and greater energy dissipation capacity. The study also reported that the 3DCP walls achieved higher load-carrying and energy-dissipation capacities than those of hollow brick, solid brick, and aerated concrete block walls. These results support the use of the diagonal tension test for evaluating the in-plane behavior of printed concrete walls. The experimental data also provide a useful basis for validating numerical models developed for this type of wall system. Although experimental studies allow structural behavior to be observed directly, specimen preparation, test setup, and measurement systems can be time- and cost-intensive. In this respect, finite element models validated against experimental results provide an effective means of systematically examining different material properties, layer configurations, wall geometries, and loading conditions. Numerical analyses also enable investigation of stress distributions, plastic deformations, and regions of damage initiation that may be difficult to monitor directly in experiments. Chortis et al. (2024) demonstrated that the structural response of 3DCP walls can be investigated using three-dimensional solid elements together with nonlinear material models. However, the mechanical characteristics associated with the layer-by-layer production process and the effects of layer interfaces need to be considered when developing a reliable numerical model. Liu et al. (2025) experimentally and numerically investigated the mechanical behavior of 3D-printed concrete walls with different cross-sectional configurations under compression, shear, and combined shear–compression loading. The results showed that increasing the number of inclined internal ribs improved the shear capacity without significantly affecting the compressive strength. The combined shear–compression strength varied nonlinearly with the axial compression ratio, reaching its maximum at a ratio of 0.4. The study also showed that voids and defects at the filament interfaces played an important role in crack initiation and propagation.

In this study, the diagonal compression test of a 600×600×150 mm 3D-printed concrete wall was modeled using ABAQUS. The nonlinear response of concrete under tension and compression, along with damage development under loading, was incorporated into the numerical model. The maximum

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load-carrying capacity and damage distribution obtained from the analysis were compared with the corresponding experimental results. Particular attention was given to how well the numerical model reproduced the diagonal cracking observed in the experiment. The main objective was to develop a finite element model that represents the experimental response with acceptable accuracy and can be used in future studies to investigate different wall geometries and layer characteristics.

2. FINITE ELEMENT MODELING

2.1. Model Geometry and Experimental Setup

In this study, the diagonal compression behavior of a 3D-printed concrete wall panel, tested in the experimental study by Mercimek et al. (2026), was modeled using ABAQUS finite element software. The wall panel had dimensions of 600 × 600 × 150 mm. The wall panel had dimensions of 600 × 600 × 150 mm. To represent the geometric characteristics of the concrete printing process, the finite element model was constructed by assembling 60 individual layers, each 10 mm thick. Consistent with the experimental test setup, rigid loading plates were positioned at two diagonally opposite corners of the FE model. **Figure 1** shows the finite element model and the loading plates used in the numerical analysis.

Figure 1. Finite element model of the wall panel and rigid loading plates.

2.2. Material Model

The nonlinear behavior of concrete was defined using the Concrete Damage Plasticity (CDP) model. The CDP model enables the representation of plastic deformation, stiffness degradation, and damage evolution associated with crushing and cracking under compressive and tensile loading. The elastic modulus, Poisson’s ratio, and compressive strength of concrete were taken as 27 GPa, 0.20, and 35 MPa, respectively. The main CDP parameters were defined as follows: dilation angle of 30°, eccentricity of

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0.1, fb0/fc0 of 1.16, Kc of 0.667, and viscosity parameter of 0.0005. The material models describing the tensile and compressive stress–strain responses, together with the corresponding damage variables, are presented in **Figure 2**.

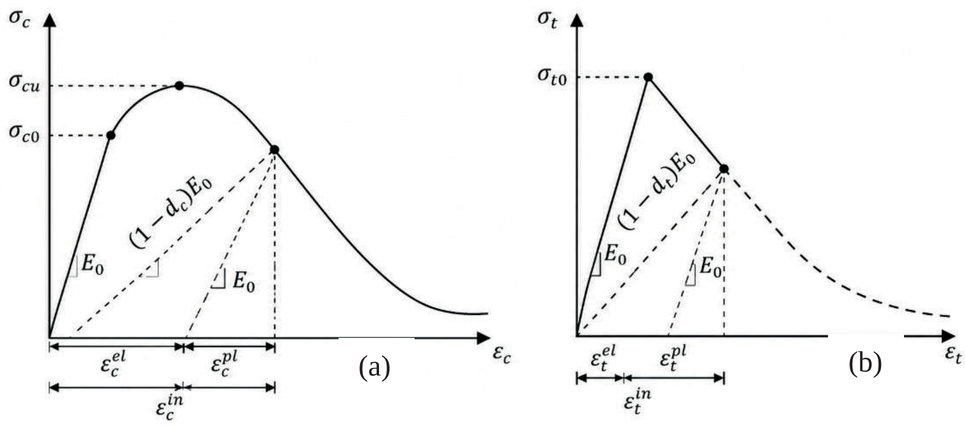

Figure 2. Schematic representation of (a) compressive and (b) tensile behavior in the CDP model.

2.3. Finite Element Mesh and Interlayer Bonding Interface

The wall panel was modeled using eight-node three-dimensional solid elements with reduced integration (C3D8R). Considering mesh-size sensitivity, an element size of 10 mm was selected, resulting in a total of 37600 finite elements for the wall model. The loading plates were modeled as discrete rigid bodies and meshed using four-node rigid shell elements (R3D4). The finite element mesh and an example of the tie constraint between adjacent layers are shown in **Figure 3**. The 60 printed layers forming the wall panel were defined as separate geometric regions. The interfaces between adjacent layers were modeled using the tie constraint approach. Relative sliding and separation were prevented at the interlayer interfaces, assuming perfect bonding between adjacent layers. Therefore, potential interlayer separation or sliding associated with the 3D printing process was not explicitly considered in the present model.

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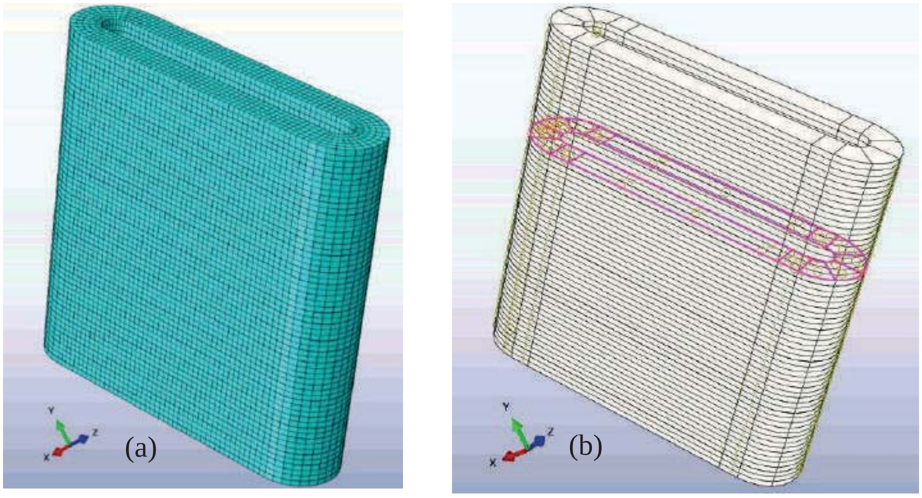

Figure 3. (a) Finite element mesh generated using C3D8R elements and (b) tie constraints defined between the printed layers.

2.4. Boundary Conditions and Loading

The interaction between the rigid loading plates and the concrete panel was defined using the General Contact approach. The normal contact behavior was modeled using Hard Contact, while the penalty friction formulation with a friction coefficient of 0.4 was used to represent the tangential behavior. All translational and rotational degrees of freedom of the lower rigid plate were fully constrained. For the upper plate, vertical translation in the loading direction was permitted, while the remaining translational and rotational degrees of freedom were constrained. Loading was applied through the reference point, coupled to the upper loading plate via a rigid-body constraint. A displacement-controlled vertical displacement of 10 mm was imposed, and a Smooth Step amplitude was adopted to minimize sudden dynamic effects. The finite element analysis was performed using the ABAQUS/Explicit solver with a total analysis time of 1.0 s. To evaluate potential dynamic effects associated with the explicit solution procedure, the model's quasi-static response was verified by monitoring the evolution of kinetic and internal energies. The energy histories were examined up to the peak load. During this interval, the kinetic energy remained considerably lower than the internal energy, indicating that dynamic effects were negligible up to the peak load and that the analysis was conducted under quasi-static conditions.

3. RESULTS AND DISCUSSION

The ability of the developed finite element model to reproduce the experimental behavior was evaluated in terms of load-carrying capacity and damage mechanisms. In the experimental study (Mercimek et al., 2026), the ultimate load-carrying capacity was measured as 166.9 kN, whereas the numerical model reached a maximum load of 176.5 kN. Accordingly, the finite element model predicted the experimental load-carrying capacity with a 5.75% difference. This close agreement at the maximum load indicates

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that the adopted Concrete Damage Plasticity model, layered-geometry approach, contact conditions, and boundary conditions provide a reasonable representation of the wall panel's ultimate load-carrying behavior. **Table 1** presents a comparison of the load, displacement, and energy dissipation capacity obtained from the experimental and numerical results.

Table 1. Finite element analysis results.

Performance index	**Experimental**	**Numerical**	**Error (%)**
Ultimate load (kN)	166.9	176.5	5.75
Displacement at peak load (mm)	9.13	2.35	74.26
Energy dissipation capacity (J)	784.3	416.2	46.91

Despite the close agreement in maximum load, more pronounced differences were observed in the deformation-based response. In the experimental study, the maximum load was reached at 9.13 mm, whereas the peak load in the finite element model occurred at 2.35 mm. This difference of approximately 74.26% indicates that the finite element model exhibited a considerably stiffer response than the experimental specimen. The tie constraint between adjacent layers prevents relative sliding and separation at the interfaces, which may restrict the interlayer deformations that can develop in the experimental specimen. In addition, local geometric imperfections, printing-induced heterogeneities, and variations in interlayer properties present in the experimental specimen were not explicitly incorporated into the idealized finite element model. Therefore, validation of the numerical model was not based on an exact match of the load–displacement response; instead, the ultimate load-carrying capacity and the dominant damage mechanisms were evaluated together. The failure load was defined as the load corresponding to a 15% reduction from the ultimate load on the post-peak branch of the load–displacement curve. The energy dissipation capacity up to the failure load was calculated as the area under the load–displacement curve using the trapezoidal method. The resulting value of 416.2 J differed from the experimental result by approximately 46.91%. The lower energy dissipation capacity of the numerical model is consistent with its stiffer response and the peak load occurring at a considerably smaller displacement. Thus, the energy-based comparison indicates that the experimental specimen exhibited greater deformation and energy dissipation capacities than the numerical model. **Figure 4** presents the vertical component of plastic strain (PE22) and the corresponding compressive damage distribution obtained from the finite element model.

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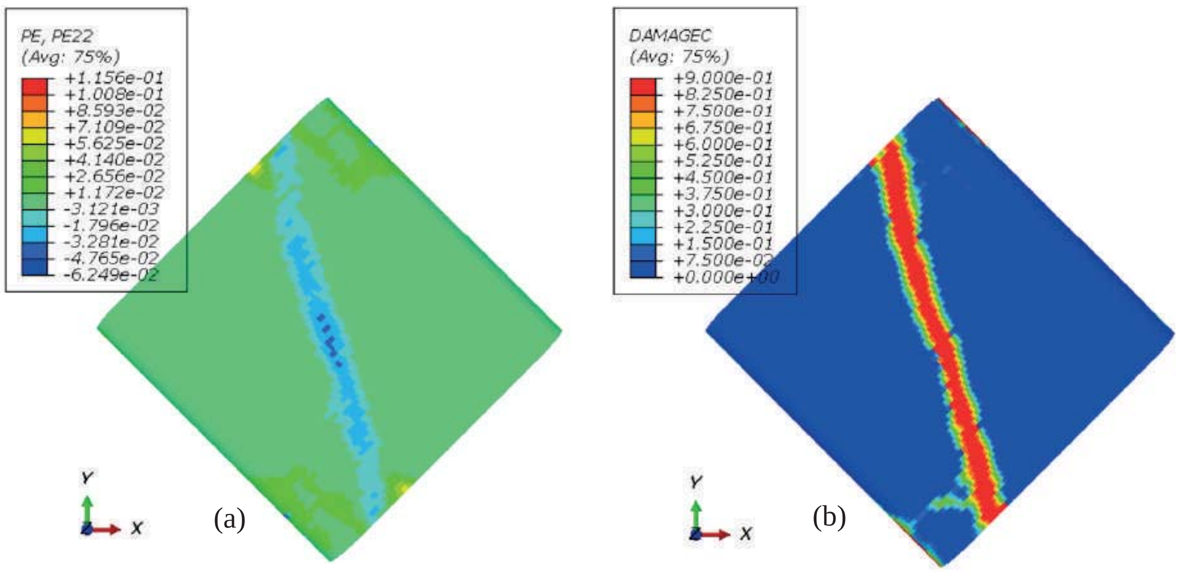

Figure 4. (a) Plastic strain in the Y-direction and (b) compressive damage distribution in the FE model.

The PE22 distribution shows that plastic strains are concentrated along a diagonal band extending from the loading to the support region. Similarly, the compressive damage distribution indicates that compressive damage is localized along the diagonal load-transfer path. This distribution is consistent with the combined stress state resulting from load transfer between the two opposite corners under diagonal compression. In particular, the local damage concentrations observed near the contact regions of the loading plates can be attributed to the buildup of compressive stresses there.

Figure 5 compares the damage mechanisms observed in the experimental study with those obtained from the finite element analysis. In the experimental specimen, the main cracks developed along the diagonal direction of the panel, forming a distinct damage band across the central region. Similarly, the numerical model exhibited tensile damage propagating diagonally across the panel, accompanied by secondary damage near the loading and support regions. Although minor differences were observed in the exact crack locations and the width of the damaged region, the similarity in the dominant damage direction and overall failure mode indicates that the numerical model adequately reproduces the experimentally observed damage mechanism.

The greater distributed tensile damage observed in the numerical model than in the experimental specimen can be attributed to the CDP formulation, in which cracking is represented by continuum damage variables rather than discrete crack surfaces. Furthermore, the assumption of perfect bonding between adjacent layers limits the representation of local opening and sliding that may occur at the interlayer interfaces of the experimental specimen. This idealization is considered to have a particularly significant influence on the numerical model's deformation capacity. Nevertheless, considering the 5.75% difference in ultimate load, together with the agreement between the experimental and numerical

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damage patterns, the developed finite element model provides an adequate approach for evaluating the wall panel's ultimate load-carrying capacity and dominant damage mechanism.

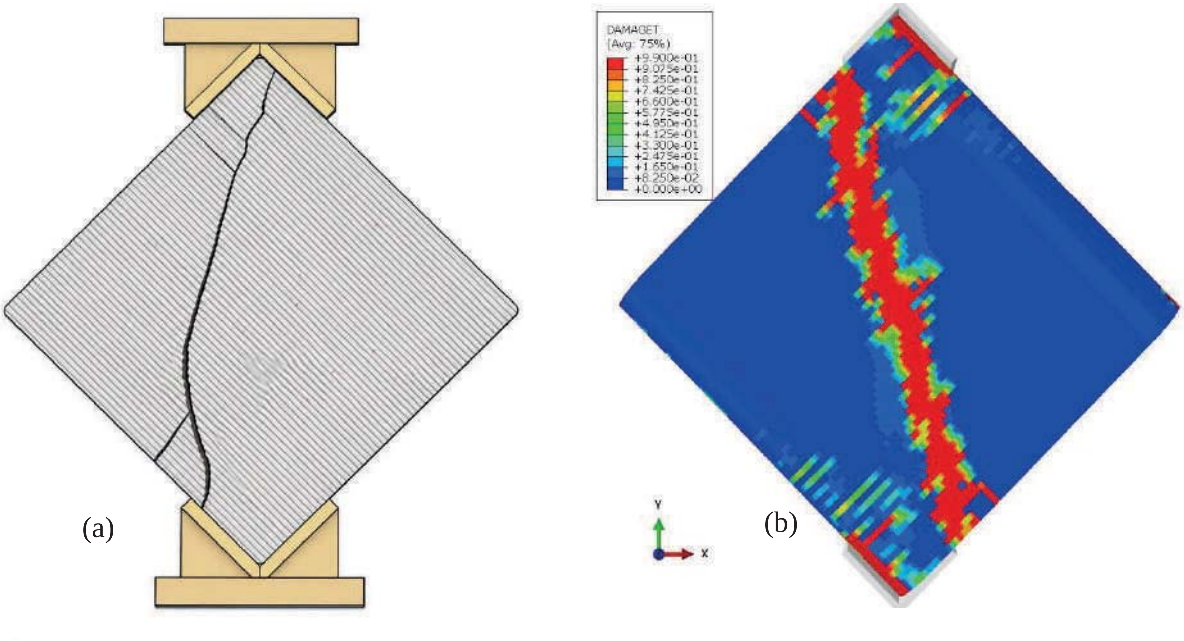

Figure 5. Damage mechanisms: (a) schematic representation of the experimental specimen and (b) finite element model.

4. CONCLUSION

In this study, the behavior of a 3D-printed concrete wall panel under diagonal compression was investigated using nonlinear finite element analysis. The results obtained from the developed numerical model were compared with experimental results reported in the literature. The numerical model predicted the ultimate load-carrying capacity with acceptable accuracy. In addition, the plastic strain and damage distributions showed that the numerical model generally reproduced the experimentally observed damage mechanism. The stiffer response of the numerical model compared with the experimental specimen was attributed mainly to the assumption of perfect bonding between the printed layers and the idealization of printing-induced irregularities. Future studies incorporating interlayer sliding and separation are expected to improve the numerical representation of the deformation capacity of 3D-printed concrete wall panels.

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