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BEHAVIOUR OF 3D-PRINTED CONCRETE WALLS UNDER LATERAL LOADING: LITERATURE REVIEW

Summary: In recent years, 3D concrete printing (3DCP) technology has found growing application in residential construction, from single and two-storey houses to apartment buildings. Nevertheless, the wider application of this technology is limited by the lack of established standards and design codes, the development of which requires a sufficiently large experimental database. Several experimental studies have performed to simulate earthquake and wind actions, which represent the most significant lateral loads on contemporary concrete structures. This paper presents a literature review of experimental investigations of the in-plane behaviour of 3DPC walls subjected to in-plane lateral loading, showing that 3DPC walls predominantly have shear failure. In addition, the review provides the current state of development of analytical models for predicting the load-bearing capacity. It was shown that they are dominantly based on masonry design standards and still require further calibration against an expanded experimental database.

Keywords: 3D-printed concrete, lateral loading, in-plane behaviour, structural walls, analytical models

PONAŠANJE 3D ŠTAMPANIH BETONSKIH ZIDOVA PRI HORIZONTALNOM OPTEREĆENJU: PREGLED LITERATURE

Rezime: Tehnologija 3D štampe betona (3DCP) poslednjih godina doživljava sve veću praktičnu primenu u stambenoj gradnji, od jednospratnih i dvospratnih kuća do stambenih zgrada. Ipak, širu primenu ove tehnologije kod viših objekata ograničava nedostatak objavljenih standarda i propisa za projektovanje, čiji razvoj zahteva dovoljno široku eksperimentalnu bazu podataka. Zbog toga je sprovedeno više eksperimentalnih istraživanja koja simuliraju zemljotres i vetar, a koji predstavljaju najznačajnija horizontalna opterećenja savremenih betonskih konstrukcija. Ovaj rad predstavlja pregled literature eksperimentalnih ispitivanja 3DPC zidova u ravni na horizontalno opterećenje i pokazano je da pretežno imaju smičući lom. Pored toga, dat je pregled trenutnog stanja razvoja analitičkih modela za predviđanje njihove nosivosti. Modeli su dominantno zasnovani na standardima za zidane konstrukcije i moraju se dodatno kalibrisati podacima iz proširene baze eksperimentalnih rezultata.

Ključne reči: 3D štampani beton, horizontalno opterećenje, ponašanje u ravni zida, konstruktivni zidovi, analitički modeli

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1. INTRODUCTION

3D concrete printing (3DCP) technology represents an innovative method for the fabrication of contemporary structures [1], [2]. The implementation of Construction 4.0 concepts within traditional construction activities has enabled the development of this sector, with numerous advantages [3]. Greater manufacturing precision, reduced material waste, decreased labour requirements, time savings, and applicability under challenging site conditions have contributed to growing interest in this technology among both industry stakeholders and the scientific community, which is actively engaged in addressing the limitations that currently hinder its wider application [4].

In addition to decorative elements and individual items of urban furniture, the first serious application of this technology was achieved through the construction of single and two-storey family houses, as well as low-rise residential buildings [5], [6]. A systematic literature review conducted by Placzek and Schwerdtner [6] recorded and evaluated 154 construction projects comprising a total of 204 buildings, realised between 2013 and 2023. In terms of geographical distribution, the largest number of buildings was constructed in the USA (34), China (27), India (12), and the UAE (10), while Germany and France each accounted for 6 buildings, and Japan and Canada 5 each.

Recent data confirm that the number of constructed houses continues to grow. As an illustration of this trend, ICON has constructed more than 100 houses to date within its "Wolf Ranch" project in Austin, Texas (USA), making this development the largest 3D-printed concrete (3DPC) residential community in the world, with plans for several hundred additional units [7]. As a further example, in April 2025, China Three Gorges University constructed a two-storey experimental building with a floor area of 100 m² in the city of Yichang, Hubei Province (China), in just 22 days [8].

It can be observed that the aforementioned 3DPC structures were constructed either by in-situ printing, by the assembly of prefabricated elements on the construction site, or by a combination of these two approaches [6]. In all cases, the structure has a layered configuration with a lattice-type cross-section, in which the cavities serve as lost formwork into which conventional reinforcement is placed and subsequently cast with concrete to form columns [5]. These elements are used to resist lateral loading, such as seismic and wind actions. In this way, the resulting structure closely resembles a typical masonry system, in which the contribution of the 3DPC infill to the load-bearing capacity of the structure has not yet been clearly established.

This question cannot currently be answered fully, because standards covering the design procedures for 3DPC structures under lateral loading have not yet been established. Established standards describe methods for testing the physical-mechanical properties, sampling procedures, printing technology, and geometric recommendations for printed elements [9]–[15]. The development of design procedures requires the establishment of an experimental database on 3DPC walls and columns under lateral loading, which constitutes one of the current research topics in the field of contemporary concrete structures.

This paper presents a literature review of experimental investigations of the behaviour of 3DPC walls subjected to in-plane lateral loading. In addition, the review provides the current state of development of analytical models for predicting the load-bearing capacity of 3DPC walls.

This literature review was conducted by searching the Scopus and Web of Science databases, using the keywords "3D printed concrete wall" and "in-plane lateral loading testing", without any restriction on publication period. The review was limited to studies reporting experimental in-plane cyclic or monotonic testing of 3DPC walls under lateral loading simulating seismic or wind actions. Based on these criteria, seven studies comprising a total of 17 tested wall specimens, were identified and are summarized in Table 1.

2. EXPERIMENTAL TESTING OF 3DPC WALLS UNDER IN-PLANE LATERAL LOADING

The first experimental investigations of 3DPC walls focused on axial compressive behaviour, in which various factors were investigated, including the height-to-length ratio, shape of cross section, reinforcement ratio, and load eccentricity [16]–[18]. Nevertheless, a comprehensive database of experimental testing of 3DPC walls under in-plane lateral loading is still lacking.

It was observed that the reviewed studies can be classified into three groups based on the tested wall type (Figure 1): 3DPC walls with RC confinement (masonry construction), FRP or textile reinforced 3DPC walls, and precast or segmented 3DPC walls, differing in interlayer bonding, base anchorage and type of reinforcement.

2.1. 3DPC WALLS WITH RC CONFINEMENT (MASONRY CONSTRUCTION)

In this approach, the 3DPC wall was combined with reinforced-concrete (RC) elements, either used as infill within a cast-in-place RC frame or provided with RC boundary or core columns at the wall edges, so that the printed material carried load together with conventional reinforced concrete. This configuration closely resembled confined masonry construction, with the 3DPC panel acting similarly to a masonry infill.

Research on the seismic performance of 3DPC walls under in-plane lateral loading started with Fu et al. [19], who tested cast-in-place reinforced-concrete (RC) frames with 3DPC infill under cyclic in-plane lateral loading. The 3D-printed infill increased bearing capacity and energy dissipation but reduced ductility and increased cracking risk at the wall–column joints, regardless of infill cross-section. Shear failure was obtained for all series of tests.

Liu et al. [20] investigated the seismic performance of single-story 3DPC walls with vertical reinforcement cages and concrete-filled core columns, calibrating a numerical model that showed good agreement with the experimental results. Cracks initiated at the interlayer interfaces and propagated into X-shaped through-wall cracks, resulting in a compression-shear failure mode. The proposed model was then used to show that a higher axial compression ratio increased the wall's bearing capacity, while the strength of the core-column concrete had little influence on the overall response.

Rao Telikicherla et al. [21] investigated the seismic performance of 3DPC walls with reinforced concrete columns on the edge, following the confined masonry system. Two full-scale walls with identical geometry were tested under two axial load levels, showing that increased axial load led to higher strength and stiffness with dominated diagonal shear failure mechanism in both cases.

2.2. FRP OR TEXTILE REINFORCED 3DPC WALLS

In this concept, the 3DPC wall was reinforced with flexible fibre-reinforced polymer (FRP) textile as an alternative to conventional steel reinforcement, with or without RC edge columns.

Zhang et al. [22] tested textile-reinforced 3DPC walls using FRP, under cyclic in-plane lateral loading. The flexible FRP textile, combined with an engineered cementitious composite (ECC) layer, provided an effective reinforcement solution for 3DPC walls. Testing of the two series (PW1 and PW2) showed a shear-sliding failure mode characterized by horizontal cracks along the interfaces between layers.

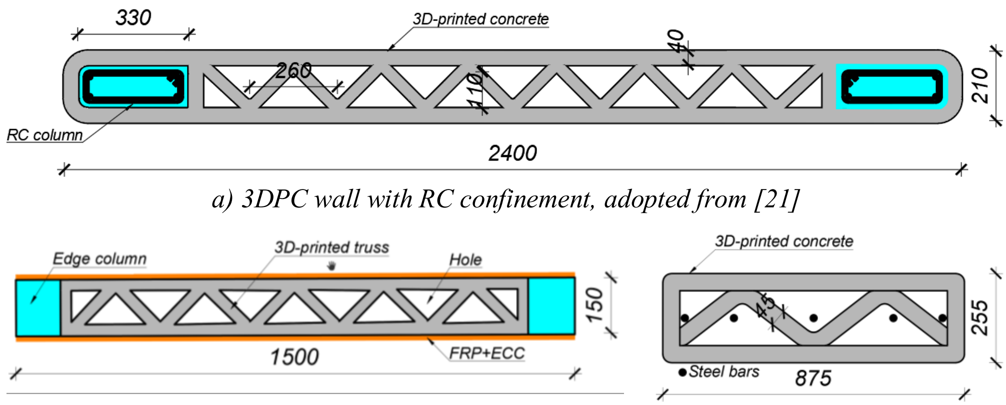
2.3. PRECAST OR SEGMENTED 3DPC WALLS

In this technology, the wall was fabricated as an unreinforced prefabricated unit or assembled from individual precast segments, without embedded conventional reinforcement, relying instead on interlayer bonding, base anchorage, or post-tensioning to provide structural integrity.

Mercimek et al. [23] tested unreinforced 3DPC walls of identical geometry under different axial load levels and loading protocols, focusing on the influence of cold joints formed between printed layers. Cold joints reduced the lateral load-bearing capacity by approximately 54% and the energy dissipation capacity by more than 200% compared to continuously printed walls, confirming that interlayer connections had a significant influence on seismic performance and failure mode. The series with cold joints exhibited sliding between layers combined with toe crushing, whereas the series without cold joints showed a diagonal shear failure mode.

Giulivo et al. [24] tested two full-scale unreinforced 3DPC walls with different base anchorage systems, a prefabricated steel connection and a conventional cast-in-place rebar dowel connection, under cyclic in-plane lateral loading. The cast-in-place anchorage reached a higher peak lateral force than the prefabricated steel anchorage, with both walls exhibiting failure characterized by three phases: elastic (flexural cracking along weak interfaces), yielding (shear-tensile interaction), and ultimate (shear-sliding).

Mitrović and Ignjatović [25] presented the possibility of segmental construction in 3DCP technology, determining the bearing capacity of an unbonded precast 3DPC segmented shear wall under monotonic in-plane lateral loading. The wall exhibited a diagonal shear failure mode without sliding between individual segments and layers.



a) 3DPC wall with RC confinement, adopted from [21]

b) FRP reinforced 3DPC wall, adopted from [22]

c) Precast segmented 3DPC wall, adopted from [25]

Figure 1: Examples of cross-sections of the reviewed 3DPC wall types

2.4. SUMMARY

More details about the geometry, reinforcement, axial load, loading type, peak lateral load, and observed failure mode of the specimens discussed above are summarized in Table 1.

Table 1: Summary of experimentally tested 3DPC walls subjected to in-plane lateral loading

Ref.	Dimensions [mm]	Type of reinforcement area and rebar [mm]	Axial load	Load type	Max. load [kN]	Failure mode
[19]	1480×1260×180 (hollow wall)	RC frame (240×240, Ø12/ Ø8); hollow wall (tie bars Ø6)	0.1 (96.2 kN)	C	900 / 500 (push/pull)	Shear (wall–column joint)
	1480×1260×180 (solid wall)	RC frame (240×240, Ø12/ Ø8); solid wall (tie bars Ø6)	0.1 (96.2 kN)	C	820 / 605 (push/pull)	Shear (wall–column joint)

[20]	1600×1200×240	RC column (6Ø10,6Ø8,Ø6@150) wall (mesh Ø6@400)	0.1 (390 kN)	C	436 / 452 (pull/push)	Diagonal shear (X shaped cracks)
[21]	1820x2400x210	RC column (330×130, Ø12)	- (45.0 kN)	C	358 / 357 (pull/push)	Diagonal shear
	1820x2400x210	RC column (330×130, Ø12)	- (250.0 kN)	C	483 / 454 (pull/push)	Diagonal shear
[22]	1500×1500×150	CFRP + ECC; GFRP bars Ø12.2; edge columns (150×150)	0.15 (354.8 kN)	C	274 / 369 (push/pull)	Shear-sliding
	1500×1000×150	CFRP + ECC; GFRP bars Ø12.2; no edge columns	0.15 (322.6 kN)	C	234 / 344 (push/pull)	Shear-sliding
	1500×1500×150	CFRP + ECC; GFRP bars Ø12.2; edge columns (150×150)	0.15 (250.6 kN)	C	135 / 201 (push/pull)	Rocking
	1500×1500×150	Unreinforced	0.15 (515.6 kN)	C	337 / 340 (push/pull)	Rocking
[23]	1250×1800×250	Unreinforced	- (20 kN)	C	25 / 25 (pull/push)	Toe crushing + Shear-sliding
	1250×1800×250	Unreinforced	- (40 kN)	C	35 / 41 (pull/push)	Toe crushing + Shear-sliding
	1250×1800×250	Unreinforced	- (40 kN)	M	40 / - (pull/push)	Toe crushing + Shear-sliding
	1250×1800×250	Unreinforced	- (40 kN)	C	81 / 80 (pull/push)	Diagonal shear
	1250×1800×250	Unreinforced	- (40 kN)	M	89 / - (pull/push)	Diagonal shear
[24]	2100×1315×350	Prefabricated steel anchorage	- (58.0 kN)	C	66 / 66 (pull/push)	Flexural + Shear-sliding
	2100×1315×410	Rebar-dowel anchorage	- (58.0 kN)	C	83 / 100 (pull/push)	Flexural + Shear-sliding

[25]	2135×875×255	5 M20 (unbonded post-tensioning)	0.06 (400.0 kN)	M	100	Diagonal shear

Dimensions: H x W x T (Height x Width x Thickness); M – monotonic; C – cyclic.

Based on Table 1, it can be observed that the dominant failure mode in the tested walls is shear failure, regardless of the type of reinforcement. In several series, the weak bond between printed layers caused the first crack to initiate at the layer interface, which subsequently propagated, leading to either a diagonal shear failure or a shear-sliding failure mode. A more ductile, flexure (rocking) response was observed only in isolated cases, confirming shear-dominated failure as the typical behaviour for 3DPC walls.

In most cases, 3DPC walls were reinforced with conventional reinforcement cages placed in boundary elements and cast in place, or used as infill within RC frames, closely resembling traditional masonry construction. This makes them easier to design using existing models, but it also reduces the automation and reusability benefits that 3DCP technology is meant to provide.

3. DEVELOPMENT OF ANALYTICAL MODELS FOR IN-PLANE LATERAL LOAD-BEARING CAPACITY

Two approaches have been developed for prediction of the capacity of 3DPC walls under in-plane lateral loading. The first is an analytical strength model proposed by Delavar et al. [26], based on the TMS 402/602 standard for concrete block masonry (CBM) walls, which was subsequently adopted by Sharma et al. [27] for the structural design of two one-story residential buildings. The modified TMS 402/602 design equation was used by Telikicherla et al. [21] to predict the bearing capacity of 3DPC walls. The second is the approach adopted by Giulivo et al. [24], in which existing masonry design procedures from Eurocode 6 [28] and Italian Structural Code [29] were applied to full-scale 3DPC walls under in-plane lateral loading and verified against to experimental test results.

Delavar et al. [26] classified 3DPC walls into two behaviour types based on the height-to-length ratio (h_w/l_w). Walls with $h_w/l_w > 1.0$–1.5 were designed to behave in flexure, allowing capacity protection against brittle shear failure and providing greater ductility. Walls with $h_w/l_w < 1.0$ were typically designed to behave in shear, since full shear protection would require an impractically large amount of reinforcement. Three failure mechanisms were defined: flexural failure, diagonal shear failure, and interlayer shear-sliding failure.

The flexural strength of the 3DPC wall was determined through sectional analysis, under the plane-sections assumption, with the entire cross-section including the 3DPC, internal RC frame, and grouted cells. The connection to the foundation was achieved through non-contact lap splices, located at the plastic hinge. Based on equilibrium of forces within the wall (free-body diagram) and by analogy with the behaviour of concrete block masonry (CBM) walls, the nominal diagonal shear strength under in-plane loading was defined as:

$$V_n = \gamma_g (V_{npc} + V_{ns}) + \Sigma V_{ncol,i} + \Sigma V_{nGC,j} \quad (1)$$

with $V_{npc} + V_{ns} \leq 4A_{nv}\sqrt{f'_{pc}}$ (2)

where: V_{npc} is the contribution of the printed concrete, V_{ns} is the contribution of the horizontal reinforcement, V_{ncol} and V_{nGC} are the contributions of the RC columns and grouted cells, respectively and γ_g is a grouting-ratio coefficient (0.75 for partially grouted or ungrouted 3DPC walls), A_{nv} is the net shear contributing area excluding the area of the columns, f'_{pc} is the compressive strength of the printed concrete.

The aforementioned prediction model [26] achieved an average error of 14.6–15.8% relative to experimental CBM wall data, considerably more accurate than the existing TMS 402/602 standard, which has an average error of 26.6–45.4%, while agreement with finite element (FE) models of 3DPC walls ranged between 8–14%. Validation on two prototype buildings [27] yielded even closer agreement between analytical and FE predictions for in-plane demands, with an average error of 2–4%, and discrepancies of up to 11% for lateral drift.

For Telikicherla et al. [21], the analytical prediction closely matched the experimental peak strength at the lower axial load level, with an error of approximately 2%, but became increasingly conservative at the higher axial load level, underestimating the experimental capacity by about 13%.

Similarly, three in-plane failure mechanisms were considered in [24]: flexural compression failure (Equation 3), diagonal cracking (Equation 4) and shear-sliding (Equation 5). Existing design provisions for unreinforced masonry [28], [29] were applied directly to experimental results obtained from full-scale unreinforced 3DPC walls, in order to assess their accuracy:

$$V_{u.P.F.} = \left(L_w t_{heg} \frac{\sigma}{2} \right) \left(1 - \frac{\sigma}{0.85 f_{ck}} \right) \frac{1}{h_{D-section}} \tag{3}$$

$$V_{u.D.C.} = \frac{L_w t_{heg} f_{ctm}}{1.5} \sqrt{1 + \frac{\sigma}{f_{ctm}}} \tag{4}$$

$$V_{u,S.S.} = f_{vko} A_c + \mu N_{ext} \tag{5}$$

where: σ is the external compressive stress, N_{ext} is the ratio of the external normal stress, $A_{D\text{-}section}$ is the actual area of the section, t_{heq} is the equivalent thickness of the section, L_w is the length of wall, A_c represent the area of the compressed zone, $h_{D\text{-}section}$ is the height from the point of load application to the D-section.

Based on these results, Giulivo et al. [24] concluded that the existing masonry design expressions for the diagonal cracking and shear-sliding failure mechanisms overestimated the experimentally determined strength, whereas the expression for the flexural compression mechanism underestimated it by approximately 40%.

4. CONCLUSIONS

Based on the presented literature review, the following conclusions can be drawn:

1. Although the application of 3DCP technology in residential construction is rapidly increasing worldwide, no standards currently exist for the design of these structures under in-plane lateral loading. This gap serves as the motivation for numerous ongoing studies on testing 3DPC elements and structures under vertical and lateral loading.
2. In all reviewed studies, the dominant failure mode is shear failure, which can develop as shear-sliding failure when caused by weak interlayer bonding or the presence of cold joints, or as diagonal shear failure mode.
3. Reinforcement is most commonly placed in the boundary elements of the 3DPC wall, which are subsequently cast in place, or in the columns of a conventional RC frame with an unreinforced 3DPC infill. Both approaches resemble traditional masonry construction.
4. The proposed analytical models for 3DPC walls under in-plane loading are based on masonry design standards, reasonable given that 3DPC walls are either infill panels between RC columns as in confined masonry, or built up from thin printed layers with bed-joint-like interlayer interfaces. However, the observed differences between experimental and predicted values obtained using existing design standards span a wide range, confirming the need for further calibration through an expanded experimental database or for the development of new design models using FE analysis.

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