SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I1P107

Volume 13 Issue 1, 76-92, January 2026

Review Article

Seismic Performance of 3D-Printed Concrete Structures: A Comprehensive Review of Material Behaviour, Geometry, and Optimization

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Received: 05 November 2025 Revised: 07 December 2025 Accepted: 06 January 2026 Published: 14 January 2026

Abstract *- The convergence of additive manufacturing and earthquake engineering is rapidly redefining the design and construction of resilient infrastructure. This review presents a comprehensive synthesis of the current state of knowledge on the seismic performance of 3D-Printed Concrete (3DPC) structures, with a particular emphasis on the role of shape optimization. 3DPC introduces unique opportunities for geometric freedom, material efficiency, and construction automation, but also poses critical challenges related to anisotropy, interlayer bonding, and reinforcement integration under dynamic loading conditions. The review classifies 3DPC structure behaviour in terms of key performance indicators, such as ductility, damping, stiffness, and energy dissipation, to examine experimental results and modelling strategies that can describe the anisotropic and interface-driven behaviour of 3DPC structures. Shape optimization is also investigated as a designing transformational technology development on the basis of computational optimization, using computational techniques, topology optimization, gradient-based approaches, and AI-based structures to operate seismic resilience and reduce material consumption. Optimized walls, shells, and lattice columns case studies illustrate high returns on the resistance against lateral loads, energy dissipation, and tuning to a frequency. Multiscale modelling and hybrid simulation, as well as machine learning-based optimization, are emerging fields of research recognized to be unique in closing the gap between material behaviour and structural performance. More so, the integration of intelligent materials with embedded sensors makes this technology more likely to be on the path of creating intelligent, adaptive 3DPC systems, which can supervise the status of the system in real time, as seismic events happen to it. Despite its encouraging nature, there are severe issues on the front of the field in the form of the lack of standards in terms of testing procedures, the limited full-scale validation, and the lack of characterization of the reinforcement functionality. This review identifies these deficiencies and offers research directions for future work, aiming to develop a single, scenario-free, performance-based design for 3DPC seismic applications. The final product of this work will assist the basic knowledge base required to advance 3DPC out of the laboratory-based innovation to working seismic infrastructure.*

Keywords *- 3D-Printed Concrete, Seismic behaviour, Construction, Geometric freedom, Energy dissipation.*

1. Introduction

1.1. Background on 3D-Printed Concrete in Structural Engineering

The 3D printing technology has become a revolution in the civil and structural engineering sector over the last ten years. One of the most promising ones is 3D-Printed Concrete (3DPC), a construction technology that requires Additive Manufacturing (AM) methods in order to produce complicated concrete components in different layers and without requiring formwork (Buswell et al. 2007). Compared to traditional casting processes, 3DPC enables a level of geometric freedom never achieved before, material efficiency, and automation in construction, dealing with long-time impractical issues in terms of the necessity of staff shortages, construction wastage, and cost efficiency.

Material rheology, printing hardware (Tay et al. 2017), and automated control systems have recently developed to a point where structurally viable 3D printed components, including walls, beams (Labonnote et al. 2016), and even full small-scale buildings (Kazemian et al. 2017) can be formed. The interest in these developments has been growing among researchers and designers, as well as among industry professionals who work to gather digital design and fast fabrication techniques. Nevertheless, being on the way to general implementation of 3DPC in field applications (Le et al. 2012), (Gosselin et al. 2016), structural performance, especially under dynamic loading, such as earthquake (Panda & Tan 2018), (Lim et al. 2012), has not merely been addressed.

1.2. Importance of Seismic Performance in Modern Construction

It has been of urgent importance that resilient infrastructure is built to withstand seismic hazards due to the more frequent and intense earthquakes globally (Shaodan Hou, Zhenhua Duan et al. 2021). Designing structures for strength, serviceability, energy dissipation, ductility, and robustness under seismic excitation is required for earthquake-prone regions (Xianggang Wang et al. 2024). Seismic design approaches traditionally have relied upon standardized materials and configurations, which may not be easily transferable as they relate to the 3DPC of interest because of its unique material anisotropy, layer-wise construction, and often novel geometrical layouts.

The safety of the 3D-printed concrete structures would require ensuring their seismic performance and consequent formation as an element of the contemporary urban space. The neglect of adequate assessment and design of these loads can lead to brittle failure mechanisms in the structure, delamination between layers, or incorrect load paths. As a result, it is necessary to have a systematic knowledge of the actions of 3DPC to cyclic and dynamic loads, even with the effect of printing parameters, infill, and geometry, as demonstrated in Figure 1. This would require combining the optimization of the structures and seismic design employing performance-based methodologies based on additive manufacturing technologies.

Over the past decade, numerous studies have contributed to the advancement of 3D-printed concrete in both materials and structural applications. Mingxu Chen et al. (2023) and Slava Markin et al. (2023) identified the key process parameters—such as print speed, layer height, and mix rheology—that govern buildability and interlayer bonding. Jianzhuang Xiao et al. (2021) and Huawei Liu et al. (2026) demonstrated that incorporating microfibers and supplementary cementitious materials can enhance tensile capacity and crack resistance in printed elements. Recent investigations by Jacek Katzer et al. (2019) and Wenxuan Zhu et al. (2025) explored the role of anisotropy in mechanical behaviour, showing significant strength variations along and across print directions. Moreover, large-scale demonstrations by Ali Kazemian et al. (2017) and Kazemian et al. (2017) proved the feasibility of 3DPC in structural components such as beams and walls. These developments collectively highlight how 3DPC has matured from a laboratory concept to a viable structural technology, yet its dynamic and seismic performance remains underexplored, providing the motivation for this review.

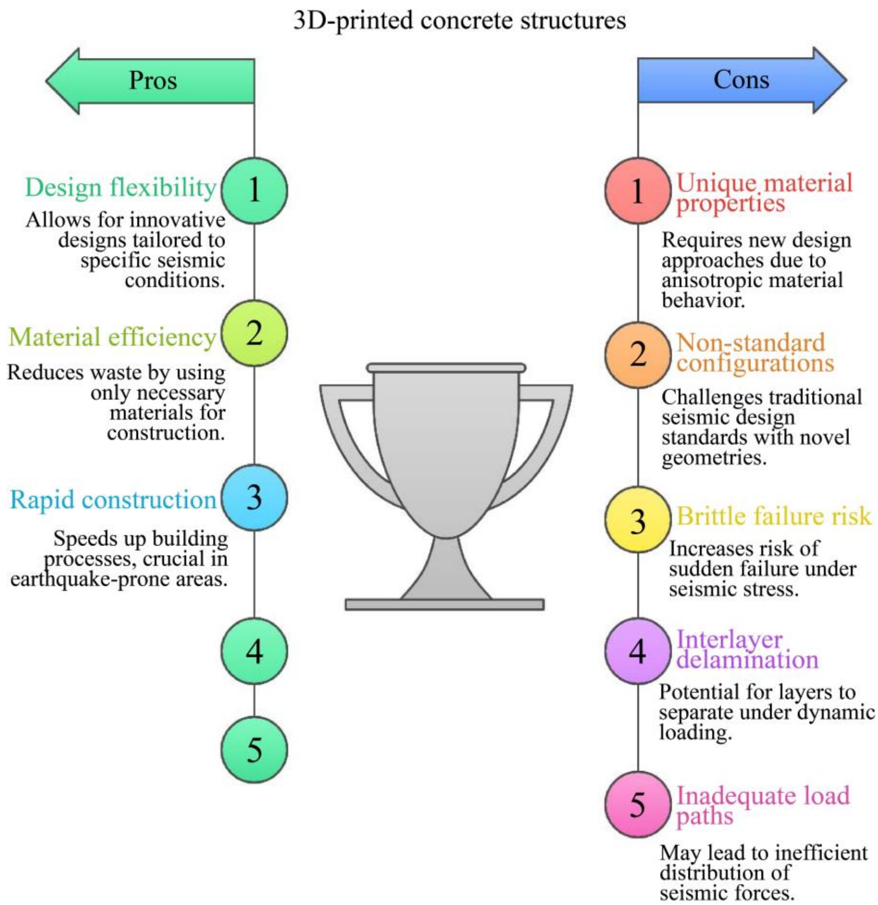

Fig. 1 Overview of factors affecting seismic performance in 3D-printed concrete

1.2.1. Identified Research Gap and Problem Statement

Despite the growing body of research on 3D-printed concrete technology, the seismic performance aspects of 3DPC structures remain inadequately understood. Current studies primarily focus on material rheology, printability, and static mechanical behaviour, with limited experimental or numerical investigations addressing cyclic and dynamic loading conditions. Moreover, the influence of print orientation, interlayer bonding strength, and reinforcement integration under seismic excitations has not been systematically characterized.

Existing models often neglect anisotropy and interface-driven failure mechanisms, leading to uncertainties in seismic design applicability. Furthermore, while shape and topology optimization have shown great potential in improving stiffness, ductility, and energy dissipation, their integration into seismic performance design frameworks for 3DPC is still in its early stages. This knowledge gap underscores the urgent need for a comprehensive synthesis that bridges material behaviour, geometric optimization, and seismic design principles to inform performance-based guidelines for 3D-printed concrete structures.

Shape optimization is an effective computational model that seeks to enhance the functionality of structural components by moulding their shapes to conform to the needs of the structural loads, as well as the reduction of material consumption. It can be used in seismic design in order to optimize the shape to improve natural vibration properties, minimize the concentration of stress, and dissipate energy. Traditional structural systems, constrained by manual fabrication techniques, often rely on rectilinear or standardized geometries. However, with the advent of 3DPC, it is now possible to realize highly customized, organic, and performance-oriented forms that were previously unfeasible.

Parametric modelling and topology optimization tools have enabled the exploration of bio-inspired and non-Euclidean geometries that offer superior stiffness-to-weight ratios and more efficient force distribution under dynamic loading (Tay, Y. et al. 2019). However, all of these advancements are in line with the possibilities of 3D printing, so that we can have the expensive geometries we want fabricated with hardly any extra cost or effort. This is the bridge between digital structural design and additive manufacturing and enables new opportunities in seismic design of concrete structures, as illustrated in Figure 2.

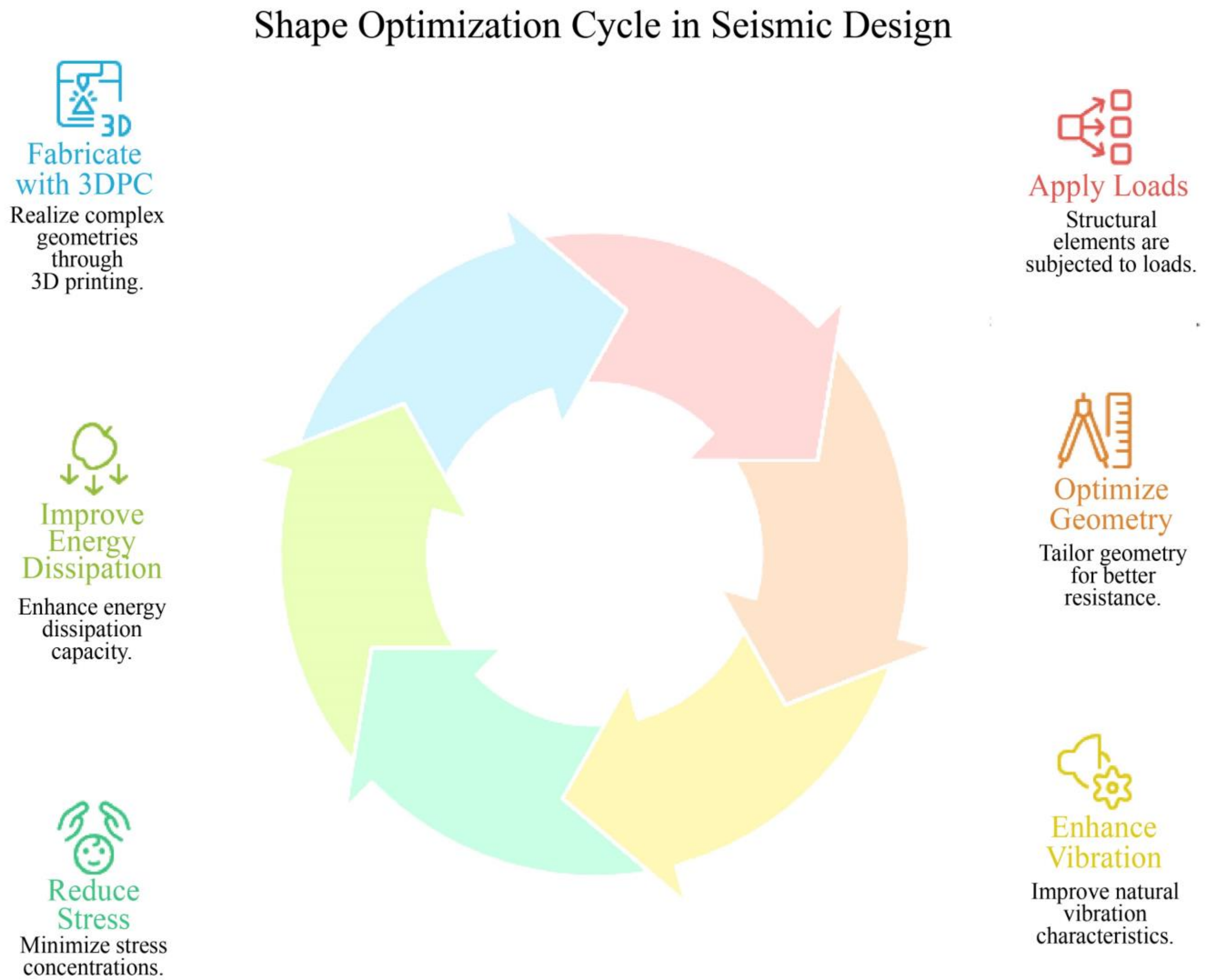

Fig. 2 Conceptual illustration of shape optimization in 3D-printed concrete structures

1.3. Objectives and Scope of the Review

This literature review aims to comprehensively examine the current state of research on the seismic performance of 3D-printed concrete structures with an emphasis on shape optimization techniques. The primary objectives are:

- How do the material composition and printing parameters of 3D-printed concrete influence its mechanical behaviour under seismic-type loading conditions?
- What are the key differences in seismic performance, particularly in ductility, damping, stiffness, and energy dissipation, between 3D-printed and conventionally cast concrete structures?
- What experimental, numerical, and modelling approaches have been used to assess the seismic performance of 3D-printed concrete, and what are their limitations?
- What research gaps and standardization challenges remain before 3D-printed concrete can be confidently implemented in earthquake-resistant design frameworks?

The scope of this review includes experimental investigations, finite element modelling approaches, and case studies focusing on the intersection of additive manufacturing, structural optimization, and seismic design. In this work, both microstructural and macrostructural aspects are considered while covering material properties, structural forms, reinforcement strategies, and testing protocols. Ultimately, the study aims to synthesize existing knowledge and to provide a critical analysis that aims to identify the future research directions to allow the safe, efficient, and resilient adoption of 3D printed concrete structures in seismically active areas (Ming Xia et al. 2016).

1.3.1. Novelty and Comparison with Existing Studies

Previous reviews on 3D-printed concrete have primarily concentrated on material mix design (Chao Liu et al., 2023; Wen Zhou et al., 2022), printing techniques and process control (Kequan Yu et al., 2021; Chao Liu et al., 2025), or mechanical performance under static loading (Natt Makul et al., 2020). However, a comprehensive evaluation of seismic performance parameters such as ductility, damping, stiffness, and energy dissipation in relation to print-induced anisotropy has not been systematically addressed. Furthermore, while separate studies have explored shape and topology optimization for structural efficiency (Siyu Liu et al., 2022; Steven J. Schuldt et al., 2021), these have rarely been contextualized within seismic design frameworks. The novelty of this work lies in its integrated review approach; it unites the domains of additive manufacturing, material anisotropy, and computational shape optimization to establish a holistic understanding of how 3DPC structures respond to seismic loads. This synthesis bridges the existing gap between material-scale research and structural-scale seismic performance, thereby providing a unique foundation for developing performance-based design criteria for 3D-printed concrete in earthquake-resistant applications.

2. Materials Used in 3D-Printed Concrete

The literature on 3DPC materials has evolved rapidly, focusing on optimizing rheology, extrusion control, and reinforcement integration. However, only a few studies have correlated these parameters with seismic performance indicators such as ductility, damping, and energy dissipation. For instance, Dirk Lowke et al. (2018) and N. Shahrubudin, T.C. Lee et al. (2019) emphasized how layer orientation and interlayer adhesion significantly affect shear and tensile strength under cyclic loading.

Vera Voney, Pietro Odaglia et al. (2021) and Habibelrahman Hassan et al. (2024) revealed that fiber-reinforced 3DPC can recover part of the energy dissipation capacity lost due to anisotropy. Similarly, Shuyi Huang et al. (2022) reported that optimized mix compositions and reinforcement layouts enhance lateral strength and hysteretic behaviour. Despite these findings, a unified understanding connecting mix design parameters, printing technology, and seismic response remains lacking, warranting the comprehensive synthesis presented in this review.

3D Printed Concrete (3DPC) uses cementitious composites specialized for the additive manufacturing process. In contrast to conventional concrete, the 3DPC mix design must satisfy demanding rheological requirements, those being extrudable, buildable, and shape-retentive. Ordinary Portland Cement (OPC), Supplementary Cementitious Materials (SCMs) including fly ash, silica fume, or Ground Granulated Blast Furnace Slag (GGBFS), and carefully selected aggregates with fine sized particles are used to make the base material, they must be able to pump and extrude with consistency (Perrot et al., 2016; Le et al., 2018). (Vaitkevičius et al., 2020.) Fresh state properties, such as workability and strength, are modulated by additives and admixtures (Vera Voney et al., 2021). The flow behaviour and setting time of the mixture are optimized using Viscosity-Modifying Agents (VMAs), superplasticizers, and retarders, which allow for continuous layer deposition without collapse (Viktor Mechtcherine et al., 2019). For seismic performance, the increasing exploration of fibres (polypropylene, basalt, or steel microfibers) is increasingly explored to improve tensile strength, ductility, and crack resistance (V. Mechtcherine, F.P. Bos et al., 2020; Egor Secrieru et al., 2017).

The reinforcement strategies being employed in 3DPC are far different from conventional steel-reinforced concrete. However, conventional steel rebar placement is difficult to use in this layer-wise printing method. Alternative solutions, including embedding continuous Fibre Reinforced Polymer (FRP) cables or in situ placement of wire mesh during printing or hybrid solutions similar to printed concrete combined with prefabricated reinforcement elements, have been researched (Dawei Liu, Zhigang Zhang et al., 2023) (Zhe Chen et al., 2021). This paper targets these methods at enhancing load-carrying capacity and energy absorption to impact seismic resilience.

2.1. Printing Techniques

The fabrication of concrete elements via 3D printing interfaces two principal 3D printing modalities: extrusion-based and powder bed.

The Extrusion-Based printing is associated with carbon deposition of a continuous bead of fresh concrete paste in a layer-wise manner through a nozzle by CNC or robotic arm. The main advantage is the capacity to print large-scale structural members with complicated geometries at a really fast pace, with no form work (S. Pessoa et al., 2021) (Qiang Wang et al., 2025). Alignment to the material's rheology is fundamentally critical, requiring that it is shear thinning such that it may be pumped and extruded, while also building up rapidly to yielding stresses, to retain shape (Hongyu Zhao et al., 2024). Structural integrity and the surface finish are variably dependent on the structural integrity and surface finish of the part upon which are based the printer's printing parameters (nozzle size, layer height, and printing speed).

Less common for concrete, but used for other cementitious materials, Powder Bed Printing is where a powder bed is selectively bound with a liquid binder to form a solid (Meruyert Sovetova et al., 2024). While suitable for small-scale, high-precision components, current limitations in buildup volume and mechanical strength (S.A. Khan et al., 2021) restrict the use of AM for structural applications. To overcome the limitations in the geometric complexity and the printing speed, extrusion approaches are hybridized to integrate with robotic arms or multi-nozzle systems (M. Sakin et al., 2017; H. Alhumayani et al., 2020). Because its fabrication is layer-wise, 3DPC is anisotropic, and its mechanical performance is driven by this property. Compressive strengths measured in experimental studies range from 20 to 70 MPa, which are similar to those for conventional concrete mixes of similar composition (Dirk Lowke et al., 2018). Meanwhile, the tensile and flexural strengths have strong directionality – both the strength and stiffness are sometimes lower in the direction perpendicular to the printing layer due to weak interlayer bonding (Zuanfeng Pan et al., 2023) (Bing Liu, Xiaoyan Liu et al., 2022).

SLA interlayer adhesion strength can be influenced by time between layers, moisture content, and rheology of the mix. This would need to be optimized to control shear strength and crack propagation under seismic loading (Le et al., 2020). Also, the 3DPC is more porous and has microcracks at the interface compared to the cast concrete, which can influence durability and fatigue resistance (Rosanna Napolitano et al., 2021). Post-processing, such as treating, impregnating, and optimizing the curing of the biomaterial, has been studied in an attempt to alleviate these issues. The modulus of elasticity for 3DPC is controlled by the printing parameters and the design of the mix, and has been reported within a wide range, with values between 15 and 30 GPa being common (Lei Ma, Qing Zhang et al., 2022). The capability for energy dissipation and damping capacity when subjected to cyclic loading, relevant to seismic applications (Guowei Ma et al., 2020), is currently an active focus of research. However, initial studies appear positive when coupling this material with adequate reinforcement design.

2.2. Differences Between Conventional and 3D-Printed Concrete in Seismic Context

From a seismic design point of view, the particularities of 3DPC forces re-evaluate certain traditional assumptions. Anisotropy and weakness Between Layers: The latter characteristic is particularly important in the case of 3DPC, considering that the layer interfaces serve as planes of weakness within 3DPC that can ultimately control the failure mode under seismic excitation in a manner not previously displayed by homogenous cast concrete. The tensile and shear strength are also anisotropic, potentially making the prediction of the crack pattern and energy dissipation more complicated (Jingchuan Zhang et al. 2019).

Freedom of Geometry: The possibility of using 3D printing to create complex optimized geometries (curved, lattice, or cellular), which are otherwise extremely challenging to achieve at scale with conventional casting techniques. This possibility of shifting the room for flexibility in order to improve the shapes in promoting ductility and stiffness distribution in order to achieve a better seismic performance (Jonny Nilimaa et. al. 2023).

Reinforcement Problems: Continuous integration of conventional rebar reinforcement in 3DPC structures, as shown in Figure 3, is challenging due to a lack of ductility and toughness. For seismic resilience, novel reinforcement techniques compatible with additive manufacturing are still critical (Shaodan Hou et al., 2021).

Material Behaviour Under Cyclic Loading: The response of 3DPC under dynamic loads differs from conventional concrete due to heterogeneity and interlayer effects. Limited experimental data suggest potential for both brittle and ductile behaviour depending on printing and curing protocols, requiring extensive experimental validation (Geert De Schutter et al., 2018). While numerous studies confirm the presence of anisotropy in 3DPC, the degree to which print orientation affects seismic response varies significantly across investigations. R.J.M. Wolfs et al. (2019) reported that specimens loaded perpendicular to print layers exhibited up to 30% lower tensile strength and markedly reduced ductility compared to parallel orientations, emphasizing the role of interfacial weaknesses. Adeyemi Adesina et al. (2020) found, however, that vertical printing orientations could sometimes mitigate premature shear failure by enhancing interlayer continuity. More recently, Junbo Sun, Farhad Aslani et al (2021) reported that trends of damping capacity and strain stiffness degradation were size-dependent, with some orientations being found to have superior cyclic energy dissipation capabilities. This diversity of findings suggests that print orientation is such that it will not only affect static strength, but also govern the dynamic response mechanism, thus making it of central importance to evaluate such different findings for performance-based seismic design of 3DPC.

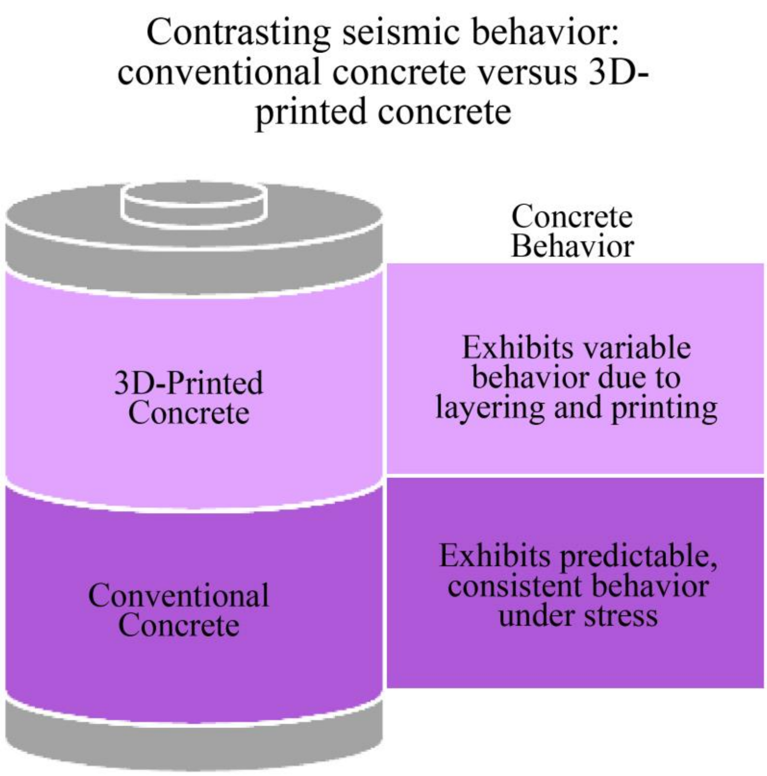

Fig. 3 Comparative visualization of structural behaviour in conventional vs. 3D-printed concrete

3. Seismic Demands and Performance Parameters

Earthquake loading, in particular, but also generally, is difficult on structural systems and must be designed to exclude life safety concerns during the loading and post-loading, and to provide serviceability during loading while also maintaining values of resources. The seismic behaviour of any structure is a complex function of these properties, their geometry, and the dynamic response of the structure.

In order to make the design processes of these new construction technologies, including 3DPC, reliable, it is necessary to have systems' requirements and performance articulated quantitatively. Key seismic performance metrics, including ductility, damping, stiffness, and energy dissipation, are discussed in this chapter, and standardized experimental and numerical methods for an evaluation of these metrics are reviewed. Performance criteria and benchmark values utilized are based on values obtained from existing codes as well as from results of research conducted in the past.

Ductility

Stiffness is described by the parameter of ductility, characterizing a structure's ability to experience large inelastic deformations without notable deterioration of the amount of load carried (Shamsaei et al., 2021). Typically, they are quantified as the ratio of ultimate displacement to yield displacement ($\mu = \Delta\_u / \Delta\_y$) (Yidong Chen, 2021). Those structures with higher ductility are able to absorb seismic energy through their plastic deformations, thereby reducing the number of seismic demands imposed on structural members of foundations.

Reinforced concrete systems develop ductility via the yielding of the steel reinforcement and a particular pattern of concrete cracking. Due to material anisotropy and weak bonding between layers in such walls, the ductility of 3DPC structures is more difficult to evaluate (Ming Xia, Jay Sanjayan et al., 2016). As printed specimens had lower ductility ratios when compared to cast concrete in experimental studies (Wen Zhou et al., 2022), this would require the use of custom reinforcement and printing parameters for increasing deformability. It has been experimentally verified that 3DPC has less ductility than standard concrete.

Damping

Damping to the vibrational phenomena properties is the mechanisms within a structure that dissipate vibrational energy during dynamic loading. The panel consists of material damping, structural damping, and energy dissipation through nonlinear hysteretic behaviour. To date, effective damping ratios (ξ) specified in seismic design of reinforced concrete structures are in the range of 2 – 5% of critical damping.

Damping characteristics are currently underexplored; however, these are expected to be material composition and printing parameter-dependent for 3DPC. Dynamic tests completed in recent years show that anisotropy and interlayer interfaces are responsible for greater amounts of microcracking and frictional energy dissipation, which may increase damping capacity. Further investigation is required to establish reliable damping values for design and simulation, however. Dynamic tests suggest that damping ratios in 3DPC vary between 3–6%, depending on print orientation and reinforcement type. While these values fall within the range of conventional RC design assumptions (2–5%), variability is higher, reflecting the influence of interlayer bonding and anisotropy.

Stiffness

Structural stiffness refers to the resistance to deformation under applied loads and influences both natural frequencies and dynamic response. It is commonly expressed as the ratio of applied force to displacement ($k = F / \Delta$). In seismic analysis, initial stiffness affects the fundamental period of vibration, thereby modulating spectral acceleration demands. 3DPC exhibits inherent stiffness anisotropy due to the layered printing process. Experimental modal analysis reveals variations in elastic modulus and shear stiffness between printing directions, affecting the global seismic response. Localized flexibility due to layer interface imperfections can change mode shapes and enhance earthquake-induced displacements.

Energy Dissipation

Absorbing and dissipating input energy through inelastic deformation and damage mechanisms is of critical importance in mitigating seismic damage through an energy dissipation capacity. Contributing to this capacity is the hysteretic behaviour of structural elements, including cyclic crack opening and closing, reinforcement yielding, and microstructural damage.

In 3DPC, energy dissipation is dependent upon material deposition and interface bonding irregularities. The potential for reduced energy dissipation is shown in Figure 4, and the cyclic laboratory loading tests on 3D printed beams and walls demonstrate reduced hysteresis loop areas compared to traditional concrete, except when techniques such as fiber reinforcement or post-processing were applied. Improving the dissipation properties, which are crucial in seismic resilience, could be achieved by optimizing material composition and by incorporating continuous reinforcement. Hysteresis-based evaluations reveal that 3DPC specimens generally dissipate 20–40% less energy compared to conventionally cast concrete under equivalent displacement cycles. However, when enhanced with steel or basalt fibers, energy dissipation capacity approaches that of RC benchmarks, indicating potential pathways to performance parity.

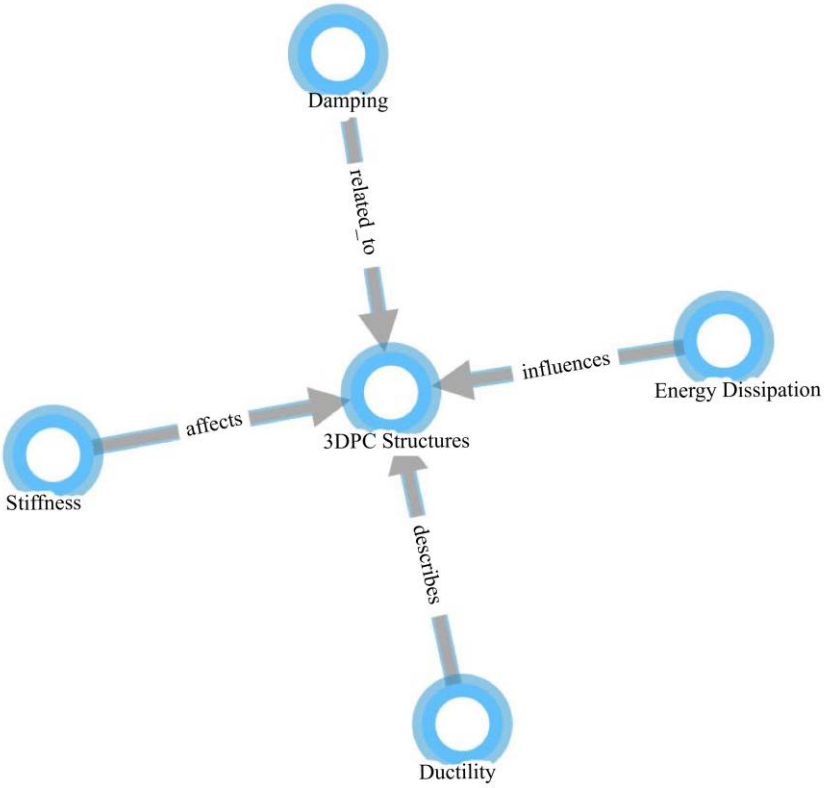

Fig. 4 Hysteresis loops of 3D-printed concrete under cyclic loading

3.1. Standards and Test Methods for Seismic Performance Evaluation

3.1.1. Shake Table Testing

Earthquake-induced ground motions are simulated on structural models to observe the dynamic behaviour under controlled conditions using the shake table experiments. Its greatest value in the consumer market is its ability to provide direct measurement of displacement, acceleration, strain, and failure modes. Shake table testing, at a variety of scales, has been performed to test 3DPC for interlayer bonding and structural integrity effects. Such advantages are that the dynamic loading is applied realistically, and complex seismic waveforms can be reproduced. High costs, scale effects, and dispersion of the exact material behaviour are the challenges.

3.1.2. Pseudo-Dynamic Testing

The pseudo-dynamic (or hybrid) testing - a numerical integration of dynamic equilibrium equations with direct physical testing of structural subassemblies (Billington, Fenves, 1991; Yuan, Chae, Xu, 202 Kequan Yu, Wes McGee et al. 2023)- was utilized for this shaking table testing. It provides dynamic fidelity at a cost-effective alternative to shake tables. With this method, the seismic performance of 3DPC elements has been evaluated for the purpose of isolating critical parameters related to the interlayer shear strength and the ductility of the element under a cyclic lateral load. It is fast enough, yet flexible for rapid parametric studies and validation of computational models.

3.1.3. Quasi-Static Cyclic Loading

Lateral loads are applied incrementally to structural specimens to simulate seismic displacement demands and observe hysteretic behaviour (Priestley et al., 1996; Lee et al., 2020). Stiffness degradation, energy dissipation, and failure mechanisms are presented using this approach. Cyclic loading tests, which are extensively used in 3DPC research, indicate degradation of bond strength at the interfaces between layers and also show a reduced post-peak load capacity compared to conventional concrete (Chao Liu, Zhan Liang et al., 2025). In addition to experimental methods, performance-based seismic design frameworks require that structural systems satisfy minimum acceptance criteria, including target ductility ratios, damping values, and energy dissipation thresholds. While such benchmarks are well established in conventional RC design codes, their direct applicability to 3DPC remains uncertain. Current experimental studies suggest lower ductility and variable stiffness retention, indicating the urgent need for codified minimum performance levels tailored to 3DPC.

4. Shape Optimization Techniques

A powerful computational approach for systematic geometric modification of structural components to meet desired performance goals, e.g., lightest weight, greatest strength, or higher seismic resilience. Shape optimization generally belongs to civil engineering, particularly 3D-printed concrete (3DPC) structures, because 3DPC uniquely exploits the freedom that additive manufacturing provides for building geometries that were unavailable with traditional construction methods (Wang et al. 2020). In this chapter, we review the fundamental principles, widely adopted methodologies, and recent progress of shape optimization pertinent to 3DPC, with a focus on enhancing seismic performance.

4.1. Principles of Shape Optimization

Structural optimization, to this end, is also often called shape optimization, design optimization, and structural topology optimization. Typically, the objective function f(Ω) subject to the constraints includes stress limits, displacement bounds, and fabrication feasibility.

$$\min_{\Omega} f(\Omega) \quad \text{subject to} \quad g_i(\Omega) \leq 0, \quad h_j(\Omega) = 0,$$

Where g_i and hj represent inequality and equality constraints, respectively. Objectives commonly include:

- Minimizing structural weight or material usage.
- Maximizing stiffness or natural frequency.
- Enhancing energy dissipation under dynamic loads.
- Reducing stress concentrations.

Constraints ensure structural safety, manufacturing constraints, and serviceability.

In 3DPC, shape optimization must also consider layer-wise printability, anisotropic mechanical behaviour, and interlayer bonding effects, complicating the constraint formulation. For gradient-based methods, sensitivity analysis is used to compute derivatives of the objective and constraint functions with respect to the shape variables. The iterative updates of the geometry toward optimal solutions are guided by these derivatives. Common approaches include:

- The Adjoint Method efficiently computes gradients for problems with many design variables.
- The Level Set Method, which represents evolving shapes implicitly and handles complex boundary changes smoothly.

Gradient methods require differentiable objectives and constraints, suitable for problems with smooth solution spaces, but can become trapped in local minima. Without utilizing gradient information, heuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Simulated Annealing (SA) are applied to explore the design space. In particular, these approaches are well-suited to highly nonlinear, discrete, or multimodal problems. Though computationally expensive, metaheuristics will provide more flexibility in incorporating manufacturing constraints specific to 3DPC and complex seismic performance criteria. Typically, in civil engineering design, there is conflict between competing factors such as cost, durability, and seismic performance. Pareto optimal solutions are identified by multi-objective optimization frameworks that trade off between these criteria. Simultaneous minimization of weight and maximization of ductility or energy dissipation is shown as an example guiding designers to select solutions according to their priorities.

4.2. Applications of Shape Optimization in 3D-Printed Concrete

4.2.1. Structural Efficiency and Material Savings

The main contribution of this study is the use of shape optimization to design structurally efficient 3DPC elements with a minimum amount of material usage. Sustainability benefits are obtained by complex lattice or cellular structures optimized for load paths, which reduce weight without sacrificing strength. Shape and topology optimization of 3D printed beams and wall panels show material savings up to 30% compared to 2D cross sections.

4.2.2. Seismic Performance Enhancement

The optimized geometries can strengthen the seismic performance of the RC structures by increasing the degree of stiffness gradient, ductility zone, and effectiveness of the energy dissipation mechanism. Furthermore, the shape optimization was used for the design of 3DPC structural components with an optimized dynamic property, such as optimized mode content, to minimize the stress around the attaching pads, as well as achieve damage localization.

4.2.3. Incorporation With Reinforcement Approaches

For the seismic characterization as well as internal reinforcement layout optimization, both geometric and layout optimization algorithms are implemented and integrated in optimization algorithms for internal reinforcement configuration for the maximum seismic efficiency. The hybrid formulation of this method shows great potential applicability to the solution of 3DPC reinforcement problems.

4.3. Challenges and Future Directions

Despite promising advances, shape optimization in 3DPC faces several challenges, which are outlined, highlighting key challenges in optimization.

4.3.1. Computational Complexity

High-fidelity nonlinear dynamic analyses required for seismic performance assessment demand significant computational resources.

4.3.2. Manufacturing Constraints

Ensuring optimized shapes are printable with current extrusion technologies requires integrating printability constraints directly into the optimization process.

4.3.3. Material Anisotropy

Accurately modelling anisotropic mechanical behaviour and interlayer effects within optimization frameworks remains an open research area.

4.3.4. Validation and Standards

Experimental validation of optimized designs and development of standardized design guidelines for seismic applications are critical for industry adoption.

Currently, the shape optimization methods are entering a new era by merging with the 3D Printed Concrete (3DPC) bodies, representing a new frontier in civil engineering, from the perspective of resilient, efficient, and sustainable civil infrastructural developments. It has the advantage that the technology of additive manufacturing does not impose any rigidity in the design, which is why we can manufacture optimized geometries that improve the seismic performance parameters, like lateral load capacity, energy absorption, and dynamic behaviour. In this chapter, the latest case studies and simulation-based research on the synergistic gain achieved from the implementation of shape optimization and 3D printing technology are fully reviewed. In addition, it explains the use of lightweight structural forms and their effect on natural frequency tuning for seismic hazards mitigation.

5. Case Studies and Simulation Approaches

Shape optimisation as part of the 3DPC structural design workflow is critically enabled by the use of simulation tools. Assessments of a nonlinear material behaviour, anisotropy resulting from printed layers, and the dynamic seismic responses using Finite Element Analysis (FEA) and related optimisation algorithms are allowed. Their purposes are advanced software platforms that nowadays include Abaqus, ANSYS, and OpenSees. Using parametric modelling and topology optimisation frameworks, iterative design cycles can be derived with shape variables updated to optimise the target performance metric, such as lateral stiffness, ductility, and energy dissipation (Siyu Liu, Bing Lu et al., 2022). This reliance on predicted behaviour is enhanced by using multi-physics simulations, considering the mechanical, thermal, and printing process parameters.

Case Study: Optimized 3D-Printed Shear Walls

Interlayer bonding and lateral load resistance of 3D printed shear walls with shape optimized geometry, Steven J. Schuldt et al. (2021). The image formation, wall thickness, and web configurations were optimised using a gradient-based optimisation framework that maximised the shear capacity and minimised the material. Under nonlinear cyclic loading, up to a 25% increment in lateral strength and 18% increment in energy absorption were calculated compared to conventional rectangular sections. Geometric tailoring optimised the walls to have a beneficial impact on the crack propagation pattern and the wall stiffness degradation through stress redistribution. Results were validated with experimental validations with scaled 3D printed specimens, and the performance of shape optimisation for applications in seismic design problems was proved.

Case Study: Lattice-Structured Columns

In the article by N. Shahrubudin, T.C. Lee et al. (2019), optimization of the Shape and topology of lattice-structured 3DPC columns was investigated and used as a part of resistant structures. A metaheuristic genetic algorithm was used to optimize and maximize the lattice node positioning and cross-sectional dimensions based on their (considering both conditions) maximization with respect to the stiffness-to-weight ratio and dynamic performance. The distributed deformation mechanisms within the lattice led to a 30% reduction in weight with no compromise on fundamental period and with an improved damping property based on results from simulations. Lightweight columns were shown to dissipate significantly more energy than traditional solid columns in pseudo-dynamic seismic simulations such as this.

Case Study: Shell Structures with Curvilinear Shapes

Level set-based shape optimization was then used by Egor Secrieru, Shirin Fataei et al. (2017) to design curvilinear shell elements manufactured with 3D printing. The aim was to achieve maximum natural frequency such that resonance would not cause structural resonance to dominate seismic frequencies. Systematic simulations exhibited a 15% fundamental frequency increase owing to the optimally curved diaphragm, which spread stresses more uniformly and reduced the stress concentrations. Shape optimization of shell forms also resulted in enhanced ductility and crack resistance under simulated earthquake loading, proving the multifunctionality of shape optimization in dynamic contexts.

5.1. Performance Gains in Lateral Resistance and Energy Absorption

Structural safety during earthquakes is greatly dependent on seismic lateral resistance. Lateral resistance is improved by shape optimization that refines geometry features, including flange thickness, web stiffeners, and boundary layer profiles to reduce stress concentrations and facilitate uniform load transfer. 3dpc elements optimized for stiffening have tailored stiffness gradients that reduce premature yielding and permit structures to survive higher lateral loads before incurring significant damage. Most advantageously, the integration with fibre or metallic reinforcement aligned along principal stress trajectories can provide much greater lateral load capacity.

The ability of a structure to dissipate seismic energy in inelastic deformation mechanisms is characterized by its energy absorption capacity. Element geometry is modified such that stable crack propagation paths are induced, plastic hinge zones are maximised, and hysteretic behaviour is facilitated. According to simulation and experimental studies, 3DPC elements, optimised for their shape, feature larger hysteresis loop areas and reduced stiffness degradation (i.e., superior dissipation capacity) compared to their non-optimised counterparts.

5.2. Lightweight Forms and Natural Frequency Enhancement

Complex lightweight geometries are made possible using additive manufacturing, not provided by traditional means. These forms are shaped for reduced self-weight and are beneficial for seismic design because inertial forces proportional to mass are reduced. High stiffness-to-weight ratios, ductility, and toughness make such cellular and lattice structures the optimized alternatives for seismic applications. In addition, significant material savings are achieved without any sacrifice of structural performance.

The natural frequencies are critical to the dynamic response and seismic vulnerability of a structure. Dawei Liu, Zhigang Zhang, et al. (2023) demonstrated the precise tuning of these frequencies using shape optimization to avoid resonance with the dominant earthquake frequency content, as shown in Figure 5, where optimized geometries attain the target frequencies. Desirable dynamic properties resulting from seismic resilience are achieved by lattice columns designed by optimization techniques and curvilinear shells or graded thickness walls. Natural frequencies decreased mitigation spectral acceleration demands and corresponding potential damage.

5.3. Challenges and Future Perspectives

In spite of the proven advantages, the approach of shape optimization to the 3DPC seismic design is challenged:

Representing Complexity: 3DPC anisotropy and nonlinear dynamic behaviour during optimization can only be represented with an accurate model and computational intensity.

Limitations in manufacturing: It is important to make sure that the shapes are optimized in order to meet the printing limits as well as the conditions of durability under seismic loading.

Code and Standard Development: The lack of standardized rules on the formats of optimized 3DPC structures restricts the implementation of 3DPC structures.

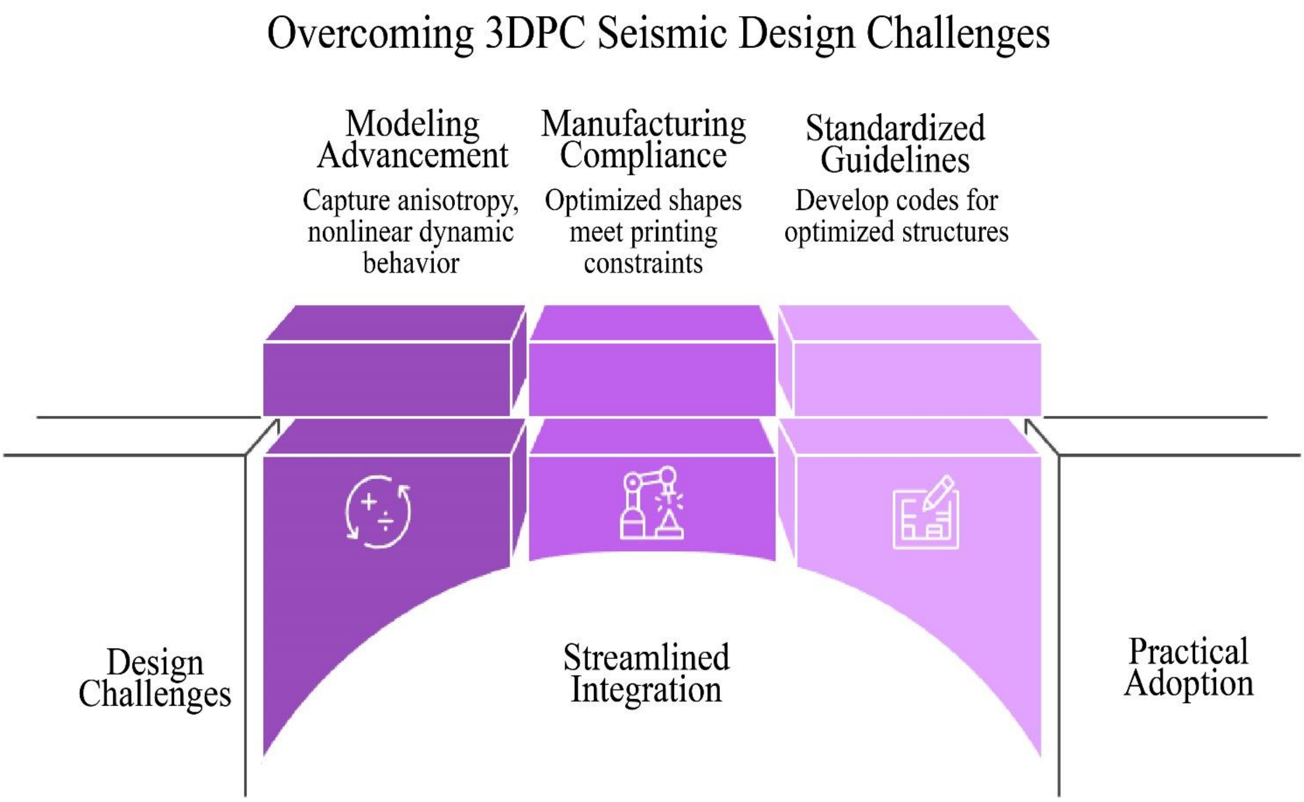

Fig. 5 Influence of shape optimization on natural frequency in 3DPC structures

6. Experimental Studies and Finite Element Modelling

The improvement in 3D Printing of Concrete (3DPC) opens the door to novel structural design possibilities, but experimental validation for bearings of seismic behaviour and robust modelling for these exciting constructions has lagged behind. In this chapter, key experimental studies on seismic response of 3DPC elements are synthesised, FEM techniques adopted for simulating their complex behaviours are reviewed, and comparative performance metrics are presented between different structural geometries and seismic loading protocols. These insights are critical to bringing fabrication technology advances in line with seismic design frameworks.

6.1. Summary of Past Experimental Studies on Seismic Response

Experimental research into 3DPC seismic performance has quickly expanded and includes studies into the performance of beams, columns, shear walls, and lattice members. Reported cyclic loading tests on 3DPC beams reinforced with steel fibres, which presented high post-peak energy dissipation as well as ductility, compared to conventionally cast specimens. With additive manufacturing, the possibility of creating complex 3DPC lattice and cellular structures is realized experimentally in pseudo-dynamic shaking table testing for the characterization of the dynamic response of 3DPC lattice columns. Additional findings indicated that loss of energy and injury tolerance in the auxetic structures in shear loading are superior as compared to their solid counterparts, and this points to a crucial point that geometrical arrangement is a significant determinant of seismic strength of the edifice.

6.1.1. Influence of Reinforcement and Interlayer Bonding

Experimental work is found to identify reinforcement methods and interlayer bonding to play important roles in seismic performance. Another research conducted by S.A. Khan, M. Koç et al. (2021) demonstrates that insufficient interlayer bonding leads to premature delamination and a decrease in the second load capacity on a lateral basis. At that, it was revealed that the control of cracks and ductility may be enhanced by means of introducing steel or fibre reinforcement, which should line the main stress directions. Some studies have demonstrated that the test results are dependent on the specimen scale and the boundary conditions. The testing of a small scale to demonstrate promise in seismic performance is scaled; scaling effects and real boundary constraints render the further structural-scale study desirable. These are critical for making extrapolations of laboratory findings to field use.

6.1.2. Finite Element Modelling Frameworks

Finite element modelling is integral for simulating 3DPC seismic response, allowing parametric studies and optimization. 3DPC constitutive models should be able to describe anisotropic behaviour due to deposition in layers and interfaces between layers. Modelling frameworks that are commonly used are:

Continuum Damage Mechanics Models

Incorporate progressive stiffness degradation and crack propagation.

Cohesive Zone Models (CZM)

Simulate interlayer delamination and interface debonding.

Plasticity-Based Models

Tackle nonlinear inelastic cyclic deformation. These models are carried out in commercial software like Abaqus OpenSees with user-defined material subroutines to capture 3DPC features. Proper modelling requires the anisotropy in the case of extrusion direction and layer interfaces. This level of modelling enhances the prediction faithfulness of crack formation and expansion because of seismic activities. Nonlinear time history and pseudo-dynamic analysis are broadly used to determine the seismic performance of 3D PC models. These approaches take into account material degradation, the formation of plastic hinges, and the dissipation of hysteretic energy. Moreover, the optimization of shape can be considered through the FEM and make structural geometries more seismically resilient through refinement.

6.1.3. Performance Comparison Across Different Geometries and Load Conditions

Comparative studies evaluate the seismic response of various 3DPC structural forms, including:

Solid vs. Lattice Structures

Lattice configurations exhibit improved energy dissipation and lower weight, beneficial for seismic performance.

Shape optimization results in curvilinear walls with reduced stress concentration and upgraded lateral strength and ductility compared to a rectangular shear wall.

Shell and Plate Structures

Thin shell forms leverage optimized curvature to increase stiffness and delay crack propagation under cyclic loads.

The seismic response varies notably with loading regimes:

Monotonic vs. Cyclic Loading

Cyclic tests reveal degradation phenomena, such as stiffness loss and crack coalescence, that are absent in monotonic tests.

Dynamic vs. Quasi-Static Loading

Dynamic shaking table tests capture inertia and rate effects critical for real earthquake scenarios.

Research proves the existence of better results between 3DPC structures that are optimized on cyclic loading, dynamic loading based on energy dissipation, and the capacity of damage. The seismic behaviour of reinforced 3DPC specimens has a significantly improved performance compared to the unreinforced specimens of all geometries and loads. Also, mechanical properties are becoming variable in terms of cementitious composites and additives, and must be incorporated in modelling and experimental design.

7. Challenges and Limitations

Although 3D-Printed Concrete (3DPC) has a great potential for innovation in the construction sector, especially having succeeded seismic applications, its mass application is not forthcoming due to some unsolved issues. These are material anisotropy and lack of proper interplanar bonding, inability to integrate reinforcement and scalability to scaled structures, and lack of standardised testing protocols and design codes. The limitations themselves have a direct influence on the assurance, repeatability, and safety of 3DPC structures, especially in dynamic loads like earthquakes. This chapter also critically reviews each of these impediments, providing the insights of the recent literature and experimental work, and the aspects that have to be focused on in research and regulation developments.

By layering up 3DPC layer by layer, anisotropy is introduced to the material, different from conventionally cast concrete. The mechanical behaviour along the printing direction is different in terms of tensile and shear strengths when compared to the perpendicular or diagonal directions of Figure 6. Such excessive and premature damage in thin crack layers has been shown experimentally to significantly drop the interfacial strength between layers, thereby weakening the overall structure under cyclic or seismic loads (30–50% lower than that of monolithic concrete.

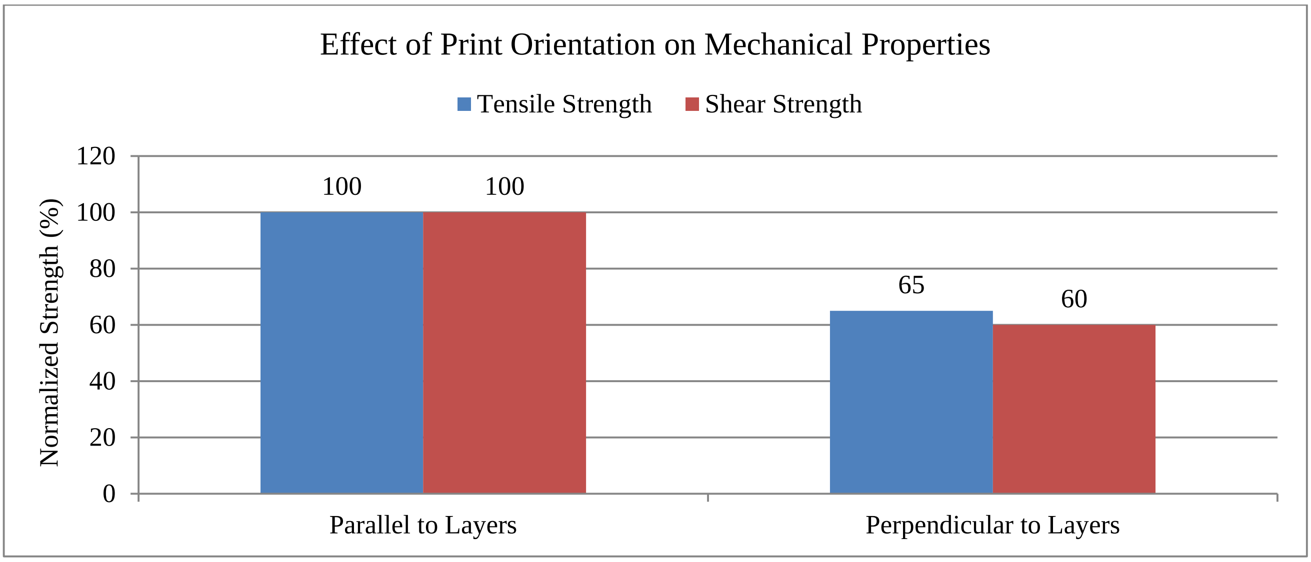

Fig. 6 Effect of print orientation on normalized tensile and shear strength in 3D-printed concrete

A critical weakness of 3DPC remains in interlayer bonding. Poor bonding and shrinkage cracking promote delamination at layer interfaces and greatly compromise the static and dynamic performance of the bridge. Under seismic loads, the problem is exacerbated by multidirectional stresses that are created along planes of weakness. As shown in Figure 7, the illustrated direction of the print path also corresponds with up to 60% less energy dissipation capacity for specimens loaded across the layers compared to along the print path, emphasized by various researchers.

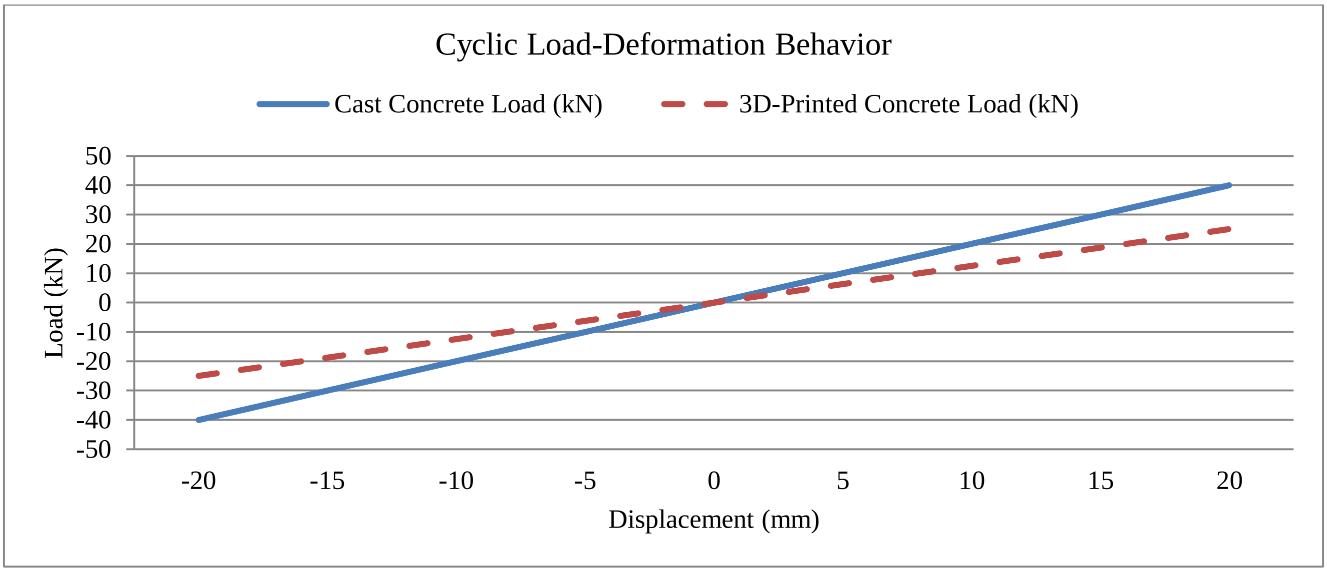

Fig. 7 Comparison of cyclic hysteresis loops for cast concrete and 3D-printed concrete specimens under displacement-controlled loading

Existing research regarding interlayer adhesion has sought to explore material modifications (e.g., pozzolanic additives), surface treatments (e.g., bonding agents applied between every layer), and process optimizations (e.g., time gap between layers and nozzle temperature control). While significant efforts have been made to implement these measures to achieve zero defects, no universal methodology exists for both small and large, and simple geometry and complex shape products; consequently, supporting the call for investigation into real-time monitoring and in-process quality control.

An objective evaluation of various methods of improving seismic resilience of 3DPC points out potential solutions that work, as well as several unresolved obstacles. The ductility and the control of crack are always enhanced by the presence of fibers, and the use of steel or basalt fiber is more efficient than polypropylene in cyclic tests. Conversely, methods of interlayer bonding, including surface activation or modifying the admixtures, are not consistent, but instead they increase shear strength and retard delamination, whereas they do not provide the lowest ductility ratios required under conventional seismic codes. Optimization of shape is proposed as an associated approach that allows for redistributing stresses and designing stress reinforcements with a goal; however, its feasibility is constrained by the cost of calculation, as well as the selection of universally established validation procedures. When combined, these comparisons suggest there is no single method that can address the anisotropy and brittleness issues in 3DPC; rather, hybrid options applying reinforcement, gaining bonding, and optimization of geometry have the greatest probability of meeting future codified seismic performances.

7.1. Scalability and Reinforcement Integration

The geometric and mechanical complexities introduced by scaling up 3DPC elements from laboratory specimens to structural components are addressed. Because such structural behaviours as cracking patterns, stiffness degradation, and strain localization do not scale linearly. Geometric distortions and thermal gradients are more prone to occur in large-scale print amounts, affecting curing rates and ultimately structural properties.

One of the most significant limitations in 3DPC is the lack of a robust method to incorporate conventional steel reinforcement, especially in critical zones requiring ductility, such as plastic hinges. Unlike cast-in-place concrete, where reinforcement cages are embedded before pouring, additive methods typically print around pre-laid reinforcements or rely on post-print insertion, both of which complicate the automation process. Various reinforcement strategies have been proposed, including:

- Integrating Fiber-Reinforced Polymers (FRP) within the material matrix.
- Printing with embedded conduits or ducts for later reinforcement.
- Hybrid systems combining 3DPC with prefabricated reinforcement cages.

In seismic regions, reinforcement is critical not only for flexural capacity but also for ductility and energy dissipation. The current state of reinforcement integration in 3DPC is inadequate for meeting the ductility demands required by seismic codes (ACI 318-19; Eurocode 8).

7.2. Lack of Standardized Testing and Codes

As of 2025, there is no internationally accepted design code or testing standard specifically addressing 3D printed concrete (3DPC) structures. Most experimental validations are conducted under customized test protocols, which makes results difficult to compare or generalize. The lack of standardized material characterization procedures also hampers the development of reliable constitutive models for simulation purposes. Existing testing of seismic performance is largely adopted from classical concrete standards, including ASTM E2126 (cyclic loading) or ISO 21581 (shake table testing). However, these protocols do not include unique 3DPC characteristics such as anisotropy, layered failure mechanisms, and scale-dependent behaviour. For example, delamination modes resulting from cyclic loading tests usually assume a 3D printed specimen. However, the lack of codified seismic provisions is a major barrier to the use of 3DPC for load-bearing and safety-critical infrastructure. Design guidelines lacking give engineers no way to calculate (for example) reduction coefficients related to anisotropic strength, ductility requirements, or energy dissipation capacity in earthquake-prone areas. However, this leads to overly conservative designs or, in turn, unsafe applications.

Preliminary work is underway by organizations such as ASTM Committee C01 and RILEM Technical Committees to develop standards (ASTM International, 2021) for additive construction materials. Protocols for structural-scale printing are also under exploration by ISO/TC 261 (Additive Manufacturing). However, it may take several years before comprehensive seismic design provisions for 3DPC are integrated into national or international codes.

Efforts are currently underway by international bodies such as ASTM (Committee C01), RILEM (TC 276-DFC), and ISO/TC 261 to develop performance-based acceptance criteria for additive construction. These include defining minimum interlayer bond strength, ductility requirements under cyclic loading, and stiffness degradation limits. However, consensus is still evolving, and until codification is achieved, performance-based design of 3DPC remains reliant on extrapolation from conventional concrete codes.

7.3. Comparing ACI 318 and Eurocode 8 with Potential Adaptations for 3DPC

Current seismic standards like ACI 318-19 and Eurocode 8 have elaborate specifications on ductility, confinement, and reinforcement detailing, as well as energy dissipation specifications in reinforced concrete structures. Nevertheless, there is a problem with their application to 3DPC straight away. An example is Eurocode 8, which characterizes ductility classes (low, medium, high) with regard to global displacement capacity and detailing of reinforcement, whereas this kind of classification fails to relate to directional ductility losses as experienced in 3DPC on account of anisotropy. In the same manner, confinement provisions and minimum reinforcement ratios of ACI 318 are based on the homogeneous concrete deposition as opposed to the 3DPC experience of a layered process of depositing materials, wherein weak interfacial bonding can cause premature shear or delamination failures.

In order to modify these codes, certain modification factors/design checks might be added. Ductility criteria in Eurocode 8 may require orientation-dependent factors to capture any interlayer weaknesses, and the ACI 318 shear strength and confinement design considerations could be augmented, with acceptance criteria for interlayer shear capacity and interlacing strategies (e.g., the addition of fibers to FRP or cage). With such adaptations in place, performance-based acceptance criteria would enable closing the gap between the traditional performance of RC standards and the specific performance of 3DPC failure mechanisms. Before such codified provisions are embraced, the engineers are left to the mercy of experimental calibration and numerical validation in regard to safe design

8. Conclusion

This research has examined the seismic performance capacity of 3D-Printed Concrete and buildings (3DPC) using the material behaviour, structural dynamics, and geometric optimum viewpoints. This integration of additive manufacturing and the performance-based seismic design is a major paradigm shift in the field of structural engineering, where there is a prospect of a more resilient, more efficient, and more data-rich infrastructure. Based on the multidisciplinary experience of materials science, computational mechanics, artificial intelligence, and earthquake engineering, the paper has provided a detailed overview of the state-of-the-art as well as revealed the important challenges and future directions.

8.1. Three Strategic Research Domains were Identified as Pivotal to Advancing the Seismic Performance of 3DPC

Multiscale modelling and hybrid testing for accurate performance prediction; AI-assisted shape optimization to harness geometric freedom; and smart materials and sensors for real-time adaptability and monitoring. Each contributes uniquely to the vision of high-performance, earthquake-resilient structures designed with and for the capabilities of digital fabrication.

8.2. Multiscale Modelling and Hybrid Testing: Toward Predictive Seismic Simulations

Mechanical behaviour and a wide range of phenomena are relevant to the 3DPC structures (mechanical behaviour), including cement kinetics and interlayer bonding on a small scale, and system-scale structural slices. Such complexity calls for the need to establish multiscale models that can be used to model material anisotropy, cumulative nonlinear damage, as well as interface degradation under the influence of seismic forces.

Recent developments in the hierarchical finite element modelling, coupled-field simulation, and interface characterisation at the meso-level have enhanced predictive power. Nevertheless, such models need powerful experimental testing, especially for new geometries and hybrid systems. Hybrid testing approaches, such as real-time sub-structuring and hardware-in-the-loop tests, have been found to be powerful approaches to fill this gap. They facilitate the seismic assessment of the 3DPC elements in contact with the digitally modelled environment, decreasing the cost of testing and increasing the fidelity.

Consequently, multiscale computational models are converging with physically validated hybrid testing, which is required to inform design codes, ensure structural safety, and promote the use of performance-based design for 3DPC technologies.

8.3. Taking Advantage of Geometric Freedom to Seismic Performance

The 3DPC allows form freedom that makes it possible to create a structural shape with an unprecedented ability to achieve structural response capacity to seismic demands. The construction of seismic design is changing its method of using the prescriptive, geometrically defined conventions towards data-driven, performance-maximizing designs with the utilization of AI and ML-based designs.

Specifically, evolutionary optimization, deep networks as generators, and reinforcement schemes are undertaking unbiased high-dimensional search in design spaces. With the tools, the topology having a high damping, ductility, and energy dissipation capacity, which is very important in seismic resilience, can be optimized. Lastly, the AI systems enhanced for performance-inclined seismic design processes will be able to learn in real-time to necessitate design geometry and its architectural combinations for specific event-driven ground motions and the limitations of materials.

Whilst giant steps in climate modelling have occurred, there are still major hurdles, such as a lack of data, interpretation, and a reliance on codes that are not in place to maintain compliance. To address this, the digital design space of the future should also include explainable AI models, but at the same time, it needs to be combined with the feedback of the real-time implicit of the structural simulations and the hybrid tests. This allows AI to augment the ability of engineers to innovate and potentially use the closed-loop design processes, where AI does not take over engineers.

8.4. Smart Materials and Other Embedded Sensors: Initiatives towards Intelligent Seismic Infrastructure

Another potential enabling factor to 3DPC resilient structures is the use of smart materials and sensory technology. The ability of Engineered Cementitious Composites (ECC), piezoresistive materials, and self-healing concretes to enhance energy dissipation, anti-cracking, and post-seismic restoration functionality is actively being studied.

This can be done in 3DPC, indicating that the functional materials can be strategically placed in only a layer-by-layer fashion or highly concentrated at high-stress regions like a joint or interface. Also, they can be used to manufacture cyber-physical systems with inherent Structural Health Monitoring (SHM) capabilities by implanting sensors, like fiber Bragg gratings, piezoelectric transducers, or MEMS accelerometers, into the printed fabric.

Real-time monitoring, diagnostics, and adaptive control systems are based on such sensor-embedded 3DPC structures. Combined with AI algorithms and digital twins, they ensure predictive maintenance, post-earthquake damage evaluation, and even automated early warning systems. Nevertheless, sensors, data management, and power supply solutions were not long-lasting, which is an unresolved issue.

8.5. Recommendations for Future Research

Based on the critical analysis of existing literature, several directions for future investigation are identified to strengthen the understanding and application of 3D-printed concrete in seismic contexts:

8.5.1. Standardized Experimental Frameworks

Develop unified testing protocols for cyclic and dynamic loading of 3DPC specimens to ensure consistent comparison across studies.

8.5.2. Material–Structure Interaction Studies

Conduct large-scale experiments to evaluate how interlayer bonding, reinforcement placement, and anisotropy collectively influence global seismic response.

8.5.3. Integration of Shape Optimization and Seismic Design

Advanced computational tools that combine topology optimization with seismic performance criteria to guide the design of energy-dissipative geometries.

8.5.4. Digital Twin and AI-Assisted Seismic Simulation

Utilize digital twin frameworks and machine learning to predict real-time seismic performance, improve failure forecasting, and accelerate optimization of printed geometries.

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