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Review Article

Bridging 3D-printed and Cast Concrete: A Review of Mechanical Bond Behavior, Composite Action, and Sustainable Protective Structures

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Abstract

New possibilities in digital construction are made possible by the combination of 3D printed concrete with traditional cast concrete, which allows for the quick fabrication of hybrid structures that blend structural efficiency, customization, and geometric intricacy. The mechanical bond behavior and composite action at the interface between cast concrete and 3D printed concrete, however, continue to be significant obstacles influencing the overall performance, longevity, and structural integrity of such hybrid systems. In order to clarify the interfacial mechanisms driving load transmission, failure modes, and bond strength development, this thorough study examines current developments in experimental techniques and numerical modelling approaches. Additionally, the research examines how printing parameters, interface preparation methods, and reinforcing tactics can improve composite activity. At the same time, the assessment assesses the application and design of 3D printed concrete for protective constructions, such as—including blast-resistant barriers, disaster shelters, and impact-absorbing walls—highlighting their performance under extreme loading conditions. Through a comparative analysis of existing findings, we identify research gaps, standardization needs, and future directions for optimizing mechanical synergy in hybrid 3D printing systems. Visual summaries including comparative tables, bond stress–slip relationship charts, and schematic illustrations of interface mechanisms are provided to facilitate deeper understanding. This review contributes to the foundation for the next generation of high-performance, sustainable, and rapidly deployable concrete structures.

Keywords

3D Printed Concrete, Cast-in-place Concrete, Interfacial Bond Behavior, Composite Action, Digital Construction, Protective Concrete Structures, Numerical Modeling

1. Introduction

1.1. Background

Three-dimensional concrete printing (3DCP) has emerged as an innovative construction technology that can dramatically reduce formwork labor, material waste, and carbon emissions compared to conventional casting [1]. By eliminating traditional formwork and enabling intricate geometries, 3DCP promises resource efficiency and faster construction, potentially accelerating progress on resilient infrastructure projects. However, the layer-by-layer nature of 3D printing

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introduces anisotropy and weak interlayer bonding, which can significantly reduce tensile, shear, and flexural strengths of printed elements. Indeed, [2] emphasizes that anisotropy and interlayer bond strength remain critical challenges impacting the mechanical properties of 3D printed concrete (3DPC).

In many hybrid applications, 3D-printed concrete is combined with conventional cast concrete – for example as permanent formwork or infill – to create composite structures. In such systems, the mechanical bond at the 3DPC–cast concrete interface governs whether the two materials act compositely or slip. Recent studies highlight that interfacial roughness and mechanical interlock are key to bond performance [3]. For instance, [3] demonstrated that the interface bond between 3D-printed formwork and cast concrete is largely due to mechanical interlock from surface roughness, and that certain mix designs (e.g. self-consolidating concrete with expansive agents) markedly improve bond strength. At the same time, weak interfacial bonding (from stratification and voids) has been shown to cause shear-slip and peeling failures in 3D-printed structures. These insights underscore the need for systematic investigation of bond behavior at the 3DPC–cast interface.

This review will examine both experimental and modeling advances on the mechanical bond and composite action of 3D-printed and cast concrete. I will also explore how these advances can inform the design of protective structures – such as coastal barriers, flood walls, and shelters – where 3D printing's rapid, formwork-free construction may be highly beneficial. Given the growing emphasis on sustainability and novel reinforcement (e.g. fiber or shape-memory alloys) in 3DCP, we will highlight new material trends and reinforcement strategies that improve performance while reducing environmental impact.

1.2. Main Objectives of the Review

The primary goals of this comprehensive review are to:

1) Survey Experimental Findings: Summarize reported experimental investigations (shear, tension, compression tests) on the interface between 3D-printed and cast concrete and on the composite action of hybrid elements.
2) Outline Modeling Approaches: Review numerical and analytical models (e.g. finite element frameworks, constitutive interface laws) developed to simulate bond behavior and composite structural response.
3) Integrate Material and Reinforcement Insights: Highlight how sustainable mixes (e.g. alternative binders, recycled aggregates) and innovative reinforcements (steel reinforcement, fiber, nano-additives, and shape-memory alloys) affect bond and overall performance.
4) Discuss Protective Structures Applications: Frame the findings in the context of protective infrastructure (coastal and flood protection, retaining walls, shelters), emphasizing design considerations unique to these structures.
5) Identify Gaps and Trends: Point out gaps in knowledge (e.g. standard test methods, lifecycle environmental assessment) and suggest directions for future research.

These objectives balance coverage of laboratory investigations and modeling efforts, and connect them to real-world engineering applications.

1.3. Scope and Limitations

This review will focus on reinforced concrete contexts involving 3D-printed and cast elements. The scope includes: (a) all general types of protective structures (e.g. coastal defenses, levees, barriers, shelters, retaining walls), without restricting to a single application, and (b) both early-stage research and implemented examples of 3DCP in civil infrastructure. We will emphasize *mechanical bond behavior* at interfaces and *composite action* under structural loads, integrating both experimental data and simulation results. The review will cover recent literature (circa 2015–2025) to ensure currency.

Boundaries include: we will not cover unrelated 3D printing media (polymers, metals) or purely architectural form-making without structural considerations. Detailed mix design of 3DPC and fluid rheology are out of scope except where directly relevant to bond behavior. We also will not attempt an exhaustive sustainability lifecycle analysis, but rather highlight key sustainable material and energy themes noted in the literature. The focus is on mechanical performance; durability issues (e.g. freeze-thaw, corrosion) will be noted briefly, but a full durability review is beyond our scope.

2. Fundamentals of 3D-printed vs. Cast Concrete

The evolution of construction methods from traditional formwork-based casting to additive manufacturing marks a paradigm shift in concrete technology. At the core of this transformation lies the distinction between cast-in-place concrete, a time-tested method, and 3D-printed concrete, a novel, formwork-free construction approach. Understanding the inherent differences in material behavior, processing methods, and structural implications is essential to evaluating their interaction in hybrid systems.

2.1. Cast Concrete: Conventional Strength and Established Practice

Cast concrete remains the cornerstone of modern construction, prized for its versatility, material uniformity, and well-established design standards. Typically poured into molds or formwork, cast concrete benefits from controlled compaction, hydration, and curing conditions. The presence of vibratory techniques helps eliminate air voids, ensuring dense packing and strong internal bonding of aggregates. These practices yield high compressive strength and reliable long-term performance under both static and dynamic loading.

However, cast concrete relies heavily on labor-intensive formwork, extended curing times, and significant material waste. While these limitations have been managed with advanced admixtures and pre-casting strategies, they present clear constraints when speed, geometry, or on-site adaptability are prioritized.

2.2. 3D-printed Concrete: Digital Precision with Novel Challenges

In contrast, 3D-printed concrete (3DPC) eliminates formwork through layer-by-layer deposition, guided by digital design models. This additive approach enables highly customized geometries, reduced material use, and the potential for automation. The mix design is tailored for extrudability, buildability, and open time—often resulting in lower aggregate content, higher viscosity, and accelerated setting characteristics.

Despite its promise, 3DPC introduces challenges absent in cast concrete. The interlayer bonding between successive prints can be a weak point, especially under shear or tensile stress. Absence of vibration during placement, anisotropic material behavior, and variable hydration profiles across layers complicate structural predictability. Moreover, 3DPC often lacks traditional steel reinforcement, raising concerns about ductility, cracking resistance, and overall robustness [20].

2.3. Comparative Implications for Composite Action

When these two systems are combined—either structurally (e.g., cast concrete poured atop or around printed elements) or functionally (e.g., printed formwork filled with cast concrete)—the interface becomes a critical zone of mechanical interaction. The material discontinuities, differences in shrinkage, rheological incompatibilities, and curing schedules can significantly influence the mechanical bond, load transfer, and composite action.

Achieving synergy between 3D printed and cast concrete requires a deliberate understanding of their distinct physical behaviors. Interface treatments, bonding agents, surface roughening, and reinforcement integration are just a few strategies researchers are exploring to ensure composite performance. A deeper examination of these strategies is necessary to harness the full structural potential of hybrid concrete systems [Table 1].

Table 1. *Key Differences between 3D Printed and Cast Concrete.*

Feature	3D Printed Concrete	Cast Concrete
Placement Method	Layer-by-layer robotic extrusion	Manual or pump casting into formwork
Material Flowability	Requires thixotropic, buildable mixtures	Typically fluid and compactable
Anisotropy	High (depends on print direction)	Low (more isotropic due to homogeneous mix)
Surface Finish	Rough, layered finish	Smooth (depends on formwork)
Reinforcement Integration	Challenging (needs tailored solutions)	Conventional (e.g., rebar, mesh)
Geometric Flexibility	High (complex shapes possible)	Limited by formwork
Construction Speed	Fast for complex, small structures	Efficient for large, repetitive elements

3. Experimental Investigation of Interfacial Bond

The interface between 3D-printed concrete and cast-in-place concrete plays a decisive role in the mechanical performance of hybrid concrete systems. Numerous experimental investigations have focused on characterizing the bond behavior at this transition zone, seeking to understand the governing mechanisms of load transfer, failure modes, and factors that influence bond strength. This section synthesizes the current body of research, highlighting key testing methodologies, material parameters, and surface preparation techniques that affect interfacial behavior [table 2].

Table 2. Summary of Experimental Studies on Interfacial Bond Behavior.

Study (Author, Year)	Interface Type	Testing Method	Key Findings
[6]	Print-to-cast	Slant shear test	Delay in casting weakens bond; surface moisture crucial
[12]	Print-to-print	Direct tensile test	Layer adhesion drops with increased interval time
[7]	Print-to-cast	Flexural test	Surface roughening improves mechanical interlock
[4]	Print-to-cast	Pull-off test	Interface angle and roughness control load transfer efficiency
[23]	Hybrid interface (3DP + cast)	Push-out test	Steel wire mesh increases composite action across interface

3.1. Test Setups and Methodologies

Experimental investigations typically employ direct shear tests, slant shear tests, split tensile (Brazilian) tests, and flexural composite beam tests to evaluate interfacial bond strength. Each method reveals different aspects of the interface behavior:

1) Direct shear tests measure pure shear capacity and are particularly effective in isolating the frictional and cohesive components of the bond [26].
2) Slant shear tests, commonly adapted from ASTM C882, introduce combined shear and compression, simulating conditions found in structural applications [27].
3) Split tensile tests provide indirect tensile strength at the interface, often revealing weak bonding or interfacial voids [12].
4) Flexural tests on composite prisms or beams evaluate the contribution of the bond to bending stiffness and crack propagation behavior [22, 16].

3.2. Influence of Surface Roughness and Interface Treatment

Surface preparation significantly affects mechanical interlock at the interface. Several studies have shown that mechanically roughened surfaces or those printed with intentional surface texture exhibit higher bond strength compared to smooth interfaces [15] Techniques such as wire brushing, grooving, or printing key geometries can improve cohesion and reduce delamination [Table 3].

In printed specimens, the printing direction and time interval between printing and casting also influence bond characteristics. A shorter delay between printing and casting allows for better chemical bonding, especially when the printed concrete remains within its open time window [14].

Table 3. Effect of interface treatment methods on bond strength.

Study	Interface Treatment Method	Material Type	Bond Strength Improvement (%)	Testing Method	Remarks
[9]	Tooth-like Interlocking Interface	3D-Printed Concrete	+42%	Direct Shear Test	Enhanced mechanical interlocking significantly improved interlayer adhesion.
[10]	Surface Moistening before Layer Deposition	3D-Printed Concrete	+18%	Tensile Bond Test	Water application promoted hydration bonding across layers.
[11]	Application of Bonding Agent	UHP-SHCC & Cast Concrete	+35%	Slant Shear Test	Chemical bonding enhanced composite action between printed and cast layers.
[5]	Surface Roughening (Grooving)	3D-Printed Concrete	+27%	Flexural Bond Test	Surface roughness increased mechanical interlock at the interface.
[12]	Fresh-on-Fresh Printing (Continuous)	3D-Printed Concrete	+50%	Layer Adhesion Test	Printing without delay maximized chemical bonding between successive layers.

3.3. Role of Material Compatibility and Print Parameters

Material compatibility, including water-to-cement ratio, admixture usage, and aggregate gradation, influences hydration continuity and shrinkage compatibility at the interface. Mismatched rheological or shrinkage properties can lead to microcracking and loss of bond strength [21].

Print parameters such as nozzle speed, layer height, and extrusion pressure also affect interlayer quality and bonding potential. When cast concrete is poured onto a 3D-printed substrate with insufficient compaction or curing overlap, cold joints may form, reducing the effective load transfer zone.

In one study by [30], the interfacial bond between a printed layer and cast concrete achieved 75–90% of monolithic strength when printed at optimal extrusion rates and cast within 15 minutes of deposition. These findings emphasize the sensitivity of bond behavior to process control.

3.4. Observed Failure Modes and Bond Stress–slip Behavior

Common failure modes at the interface include adhesive failure, cohesive failure in the weaker substrate, and interface delamination under shear or tensile stress. In most experimental settings, failure initiates at the interface but propagates along the weaker path, often within the 3D-printed layer due to its anisotropy and lower density [31].

Bond stress–slip relationships, often derived from direct shear or push-out tests, reveal nonlinear behavior characterized by an initial elastic phase, followed by softening and residual friction.

4. Numerical Modeling of Interfacial Behavior

While experimental investigations provide crucial insights into the interfacial bond characteristics between 3D-printed and cast concrete, numerical modeling offers a complementary avenue to interpret, predict, and optimize composite action across a range of structural configurations. Computational models enable researchers to simulate stress distribution, crack development, and failure mechanisms at the interface, often under varying geometric, material, and loading conditions. This section outlines the current modeling strategies used to simulate interfacial bond behavior, highlighting the capabilities and limitations of various numerical approaches.

4.1. Finite Element Modeling Approaches

Finite Element Analysis (FEA) has become the predominant tool for simulating the bond behavior at concrete interfaces. Different modeling strategies have been developed depending on the complexity of the interface, the expected failure mechanism, and the desired level of accuracy [table 4].

Table 4. *Modeling Techniques for Simulating Bond Behavior.*

Modeling Approach	Software/Platform	Interface Type	Strengths	Limitations
Cohesive Zone Modeling (CZM)	ABAQUS, ANSYS	Print-cast	Captures delamination, crack initiation	Needs calibrated parameters
Contact Elements	ANSYS, LS-DYNA	Print-cast/print-print	Simple implementation, contact friction effects	Limited accuracy under dynamic loading
Extended FEM (XFEM)	ABAQUS	Print-cast	Simulates crack propagation at interface	Computationally intensive
Concrete Damage Plasticity	ABAQUS	Print-cast	Captures nonlinear behavior of both materials	Requires calibration of damage evolution curves
Machine Learning-Assisted FEM	MATLAB + FEM	Print-cast	Data-driven, adaptive prediction of interface failure	Needs large training data

In early studies, researchers often used perfect bond assumptions, where no relative slip between the 3D-printed and cast concrete was allowed. While simple, this approach neglects the real interfacial mechanics and is unsuitable for capturing debonding or delamination [27]. More refined models incorporate cohesive zone models (CZMs), which define the interface using traction–separation laws and can simulate the initiation and propagation of interfacial cracks [28].

For instance, in the work of [29], a bilinear cohesive zone law was implemented in ABAQUS to simulate the interfacial bond behavior observed in slant shear tests. The model captured peak bond strength, initial stiffness, and post-peak softening behavior with high accuracy when calibrated against experimental data.

4.2. Interface Element Modeling and Contact Mechanics

A widely adopted strategy in FEA is the introduction of interface elements between the 3D-printed and cast concrete domains. These zero-thickness elements allow for relative displacement and separation under applied loads. Models can be defined using frictional contact laws (Coulomb-based) or traction–separation laws (cohesive laws), depending on whether the interface is expected to behave primarily in frictional slip or cohesive failure [14].

The accuracy of such models depends on proper calibration of parameters such as normal and shear stiffness, fracture energy, and interface strength. These parameters are typically derived from experimental shear or pull-off tests. Sensitivity analyses have revealed that variations in interface stiffness and fracture energy significantly influence the predicted load–slip behavior and failure mode [17].

4.3. Multi-scale and Material Heterogeneity Considerations

Given the layered nature of 3D-printed concrete and its anisotropic behavior, multi-scale modeling approaches have gained attention. Some researchers have used mesoscale models, which explicitly represent the mortar layers, interlayer voids, and printed interfaces, while others adopt homogenized macroscale models for larger structural simulations [20].

At the mesoscale, Discrete Element Methods (DEM) and Lattice Models have been employed to simulate crack initiation and propagation at the interface. These methods can capture the influence of surface roughness and local heterogeneities more effectively than continuum-based models [12].

4.4. Validation Against Experimental Data

Validation of numerical models is essential to ensure reliability and transferability of simulation outcomes. Most studies compare predicted bond strength, crack paths, and load–slip responses with those obtained from slant shear, flexural, or push-off tests.

For example, a study by [21] successfully validated their CZM-based model with experimental slant shear results, showing less than 10% deviation in bond strength predictions. The model also accurately captured the transition from cohesive failure within the printed layer to adhesive failure at the interface, depending on the surface condition and curing delay [table 5].

Table 5. *Summary of validation studies comparing numerical predictions and experimental outcomes.*

Study	Numerical Method	Experimental Setup	Key Findings	Deviation between Model and Experiment (%)	Remarks
[15]	Finite Element Analysis (FEA) with Cohesive Zone Modeling	Direct Tensile Tests on 3D-Printed Concrete	Numerical predictions accurately captured crack initiation and propagation patterns.	<10%	Suggested the importance of interface properties calibration.
[18]	Nonlinear FE Modeling (ABAQUS)	Shear Bond Tests between Printed and Cast Concrete	Numerical models predicted peak bond strengths close to experimental data.	8–12%	Highlighted influence of element size and mesh refinement.
[9]	XFEM (Extended Finite Element Method)	Tooth-Interface Shear Tests	XFEM successfully simulated interfacial failure mechanisms.	5–9%	Effective for simulating complex crack patterns at interfaces.
[19]	Coupled Hygro-Mechanical Modeling	Tensile Testing of Layered 3D Concrete Specimens	Model captured both strength and shrinkage-induced cracking behaviors.	<7%	Emphasized the necessity to include moisture transport phenomena.
[10]	Micro-Mechanical Discrete Element Modeling	Interlayer Tensile Tests	Micromechanical models matched well with layered failure modes observed experimentally.	6–11%	Suggested good potential for layer-by-layer optimization modeling.

4.5. Challenges and Future Modeling Directions

Despite progress, challenges remain in modeling 3DPC–cast interfaces accurately. These include:

1) Capturing time-dependent effects like creep, shrinkage, and curing overlap.
2) Modeling interfacial behavior under dynamic or cyclic loads.
3) Accounting for environmental degradation and long-term performance.

Emerging directions include the use of machine learning-assisted models to predict interface properties based on material and process inputs, and phase-field models to simulate progressive damage at the interface in a thermodynamically consistent manner [8].

5. Numerical and Analytical Modeling of Composite Action

Understanding and predicting the composite behavior between 3D-printed concrete (3DPC) and cast-in-place concrete is critical for optimizing the performance of hybrid structural systems. This section presents an integrated review of numerical and analytical models developed to simulate the composite action, bond transfer mechanisms, and structural response of such systems. Emphasis is placed on capturing the distinct material behavior, interaction mechanics, and failure modes under various loading scenarios.

5.1. Composite Action in Hybrid Concrete Systems

The effectiveness of composite action depends primarily on the quality of the interface, the compatibility of material properties, and the loading type. In hybrid systems combining 3DPC and cast concrete, the composite action can be classified into three types: full composite, partial composite and non-composite behavior [table 6]. Full composite action implies perfect bond and strain compatibility, while partial composite action involves slip and deformation at the interface [14].

Table 6. Mechanical Performance of Hybrid 3DP + Cast Elements from Recent Studies.

Study	Structural Element	Loading Type	Key Outcome
[8]	Wall with cast footing	Axial compression	Composite section increased load capacity by ~25%
[7]	Beam with 3D printed top	Bending	Failure occurred at interface; enhanced by surface keying
[9]	Printed vault + cast ring	Lateral load	Arching action preserved; hybrid connection effective
[13]	Protective barrier (U-shaped)	Impact	Fiber-reinforced cast concrete improved post-impact integrity
[11]	Shelter corner joints	Seismic simulation	Hybrid joints dissipated more energy than monolithic types

5.2. Numerical Strategies for Composite Behavior

Advanced finite element (FE) models have been developed to simulate the composite behavior of 3DPC–cast interfaces, integrating interfacial constitutive laws, material anisotropy, and geometric discontinuities. Most studies adopt 3D solid modeling with nonlinear material behavior, incorporating concrete damage plasticity (CDP) models and cohesive zone modeling at interfaces.

For example, [7] developed a detailed 3D finite element model in ABAQUS incorporating cohesive traction–separation laws and CDP material models to simulate composite beam behavior under flexural loading. Their simulation captured crack initiation at the interface and progressive delamination, closely matching experimental load-deflection curves [table 7].

Other researchers (e.g., [32]) introduced embedded interface elements and calibrated stiffness and fracture energy parameters to simulate partial composite action. Their findings indicated that increasing interface roughness and reducing time delay improved stress transfer and delayed debonding.

Table 7. Overview of FE modeling approaches for composite hybrid elements.

Study	Mesh Type	Interface Law/Model	Software Platform	Validation Result	Remarks
[17]	Hexahedral Mesh	Cohesive Zone Model	ABAQUS	Good agreement with	Interface parameters critically

Study	Mesh Type	Interface Law/Model	Software Platform	Validation Result	Remarks
	(structured)	(traction-separation law)		tensile test results; deviation <10%	influenced bond strength prediction.
[18]	Tetrahedral Mesh (unstructured)	Bilinear Cohesive Law	ANSYS	8–12% deviation from experimental shear strength	Mesh refinement was key for crack path prediction accuracy.
[9]	Hybrid Mesh (Hex + Tet elements)	XFEM with embedded discontinuities	ABAQUS	High fidelity in simulating shear failure patterns; deviation ~5–9%	XFEM captured crack initiation and propagation without remeshing.
[19]	Hexahedral Mesh (fine grid)	Coupled Hygro-Mechanical Interface Model	COMSOL Multiphysics	<7% deviation for shrinkage and strength prediction	Integration of moisture transport enhanced model reliability.
[10]	Discrete Element Method (DEM) Mesh	Micro-Mechanical Contact Law	PFC3D (Particle Flow Code)	6–11% deviation from layered tensile test results	Micromechanical simulation effectively captured interfacial debonding behavior.

5.3. Analytical Models for Interface Shear Transfer

Analytical models provide simplified tools to predict interfacial shear transfer and global structural response. Classical shear-friction models, adapted from precast and monolithic construction have been modified for 3DPC–cast concrete interfaces. These models estimate ultimate shear capacity as a function of interface roughness, cohesion, friction, and clamping stress [table 8].

Proposed an analytical formulation based on Mohr–Coulomb failure criteria, incorporating interface cohesion and effective normal stress derived from casting pressure and shrinkage effects. [33] Their model was validated against push-off and slant shear test results and showed good correlation, especially for rough and moist-cured interfaces.

Another approach is the partial interaction theory, where relative slip between the printed and cast sections is explicitly modeled. Using compatibility and equilibrium conditions, simplified expressions for stress and strain distributions can be derived [13].

Table 8. *Comparison of analytical models for hybrid interfaces: governing equations, assumptions, and application domains.*

Analytical Model	Governing Equations	Key Assumptions	Application Domain	Remarks
Linear Elastic Fracture Mechanics (LEFM)	Gc=KIC2EG_c = \frac{K_{IC}^2}{E}Gc =EKIC2	Interface behaves elastically up to failure; small-scale yielding	Initial cracking and fracture initiation in brittle 3D printed interfaces	Effective for early-stage crack prediction but limited for large deformations.
Cohesive Zone Model (CZM)	σ=f(δ)\sigma = f(\delta)σ=f(δ), where σ\sigmaσ is traction and δ\deltaδ is displacement	Nonlinear stress–displacement relationship; gradual failure	Progressive debonding and crack propagation along printed-cast interfaces	Captures full fracture process but requires careful calibration.
Shear-Lag Model	τ(x)=dσ(x)dx·E2G\tau(x) = \frac{d\sigma(x)}{dx} \cdot \frac{E}{2G}τ(x)=dxdσ(x)·2GE	Uniform shear stress transfer; negligible bending effects	Bond-slip behavior between printed and cast layers	Useful for short-span, strongly bonded interfaces.
Fracture Process Zone (FPZ) Approach	σ(δ)=σc(1−δδc)\sigma(\delta) = \sigma_c (1 - \frac{\delta}{\delta_c})σ(δ)=σc (1−δcδ) for δ<δc\delta < \delta_cδ<δc	Presence of a fracture process zone at the interface; softening behavior	Post-cracking behavior modeling in printed–cast composites	Suitable for quasi-brittle material behavior such as concrete.
Extended Interface Plasticity Model	σ=k(δ−δp)\sigma = k (\delta - \delta_p)σ=k(δ−δp) for plastic displacement δp\delta_pδp	Interface exhibits both elastic and plastic response	Large deformation and post-yield behavior in protective structures	Enables modeling of ductile failure modes often missed by simpler models.

5.4. Hybrid Numerical–analytical Approaches

Some researchers have proposed hybrid frameworks that couple analytical equations with localized numerical models for critical regions, particularly the interface. For example, a hybrid FE–analytical approach by [33] used FE modeling to simulate local bond-slip behavior while using beam theory and composite beam equations for global analysis. This allowed significant reduction in computational time while maintaining predictive accuracy [table 9].

Table 9. Summary of hybrid modeling approaches and their performance compared to full FE analysis.

Hybrid Approach	Description	Performance Compared to Full FE	Advantages	Limitations
Semi-Analytical + FE Coupling	Analytical bond-slip laws incorporated into local FE elements	~15–20% faster computation; ~5% deviation in stress predictions	Balances computational speed and accuracy	Limited in capturing complex failure modes
Multi-Scale Modeling (Microscale Interface + Macroscale Structure)	Fine-scale modeling of the interface, coarse-scale elsewhere	~30% reduction in computation time; deviation <8% for strength and failure modes	Captures microstructural effects without full computational cost	Requires careful scale transition calibration
Discrete Interface Elements (Cohesive Elements) + Continuum Bulk Elements	Explicit interface elements model debonding; surrounding concrete as continuum	Very close (<3% deviation) to full FE; ~20% faster	High fidelity bond failure modeling	Mesh dependency at the interface requires refinement
XFEM Simplified Interface + Elastic Bulk	Interface fractures modeled using enriched elements without remeshing	Deviations within ~5%; large crack propagation captured well	Efficient simulation of crack initiation and growth	Less effective for highly nonlinear post-failure behavior
Analytical Stress Redistribution + FE Damage Zones	Analytical stress profiles guide placement of FE damage zones	~25–30% faster simulation with ~10% strength prediction deviation	Reduces model complexity while capturing key failure behaviors	Not suited for highly heterogeneous or anisotropic materials

5.5. Challenges and Future Directions

Despite progress, modeling the composite action of 3DPC–cast systems remains challenging due to:

1) Limited standardization of interface characterization.
2) Complex time- and moisture-dependent interface properties.
3) Lack of data for long-term behavior, cyclic loading, and fatigue.

Future research should focus on developing probabilistic models for interface variability, machine-learning-based surrogate models for rapid prediction, and digital twin frameworks for real-time structural monitoring and design optimization.

6. Applications in Protective Concrete Structures

The integration of 3D printing with cast-in-place concrete has opened new avenues for designing and constructing protective structures that are not only robust and modular but also optimized for resource efficiency, rapid deployment, and adaptive geometries. Protective concrete structures—such as barriers, blast-resistant walls, military fortifications, shelters, and impact-absorbing installations—demand high mechanical integrity, controlled failure mechanisms, and often complex geometries. This section explores the current state and future potential of hybrid 3D printed–cast concrete systems in such applications, drawing from experimental, numerical, and field-based studies.

6.1. Design and Performance Criteria for Protective Structures

Protective concrete structures are typically designed to resist impact, blast, and projectile loading. Key performance criteria include energy dissipation, crack control, post-peak ductility, and structural continuity. The integration of 3D printing allows for form customization to guide stress flow and reduce stress concentrations under dynamic loading, while cast-in-place concrete offers additional reinforcement integration and monolithic behavior [table 10].

According to [5]. structures like 3D printed barriers can achieve higher energy absorption through tailored cellular or infill geometries. When bonded with cast concrete overlays, these hybrid systems can exhibit improved stiffness and resistance to delamination under blast-like loads.

Table 10. Key mechanical and performance requirements of protective concrete systems.

Performance Parameter	Target Requirement	Typical Test Methods	Relevance for 3D Printed-Cast Composite Systems
Compressive Strength	>50 MPa for structural applications; >80 MPa for blast resistance	ASTM C39 / EN 12390-3	Essential for resisting static and dynamic loading in protective barriers
Flexural Strength (Modulus of Rupture)	>7 MPa for load-bearing panels	ASTM C78 / EN 12390-5	Critical for improving resistance to bending, impact, and deformation under blast waves
Bond Strength at Interfaces	≥ 1.5 MPa or 80% of parent material strength	Direct shear tests; pull-off tests (ASTM C1583)	Vital for maintaining integrity between printed and cast concrete layers under extreme loading
Fracture Toughness	K_IC > 0.5 MPa√m (depending on application)	Three-point bending fracture tests	Enhances energy absorption and crack resistance, crucial under dynamic impacts
Impact Resistance	No spalling or delamination under moderate impact loading	Drop weight impact test (ACI 544-2R)	Indicates capacity to absorb shock without catastrophic failure
Durability (Freeze-Thaw Resistance, Chemical Attack)	Loss of mass <5% after 300 cycles (freeze-thaw); High sulfate resistance	ASTM C666 (freeze-thaw); ASTM C1012 (sulfate attack)	Ensures long-term performance in harsh environments typical for protective installations
Fire Resistance	Integrity ≥ 2 hours at 1000°C exposure	ISO 834 / ASTM E119	Provides resilience under fire hazards or thermally induced blast events
Blast Resistance (Dynamic Response)	Ability to absorb and dissipate energy without rupture	Arena tests; high strain-rate testing (Split-Hopkinson Pressure Bar)	Core requirement for military shelters, barriers, and fortifications

6.2. Experimental Case Studies on Protective Applications

Several studies have reported on experimental validation of 3DPC in protective structures. [24] Investigated the response of 3D printed cementitious panels subjected to projectile impact. Their tests revealed that incorporating fiber reinforcement and cast-in-place backings significantly enhanced impact resistance, reducing rear-face spalling and increasing energy absorption by up to 40% [Table 11].

Similarly, [25] tested 3D printed U-shaped barriers with cast concrete cores against high-velocity impact. The hybrid specimens showed cohesive failure at the interface but maintained structural integrity beyond the threshold impact velocity, highlighting the importance of bond quality.

Table 11. Summary of experimental studies on hybrid protective structures and key findings.

Study	Materials Used	Structural Type	Test Method	Key Findings
[5]	3D printed concrete + cast UHPC overlay	Blast-resistant wall panels	Shock tube blast testing	Hybrid walls with cast overlays achieved 25–30% greater blast energy dissipation compared to monolithic printed elements.
[21]	3D printed geopolymer concrete + fiber-reinforced cast layer	Protective shelter modules	High-velocity impact testing	Interface bond strength was critical; fiber reinforcement improved post-cracking integrity under impact.

Study	Materials Used	Structural Type	Test Method	Key Findings
[12]	3D printed normal concrete + steel mesh reinforced cast overlay	Barricade elements	Static and dynamic flexural testing	Hybrid composites showed 18% higher flexural strength and enhanced crack control relative to plain printed structures.
[32]	3D printed ultra-high strength concrete + cast conventional concrete	Modular protection units	Drop weight impact tests	High stiffness mismatch led to interfacial cracking; optimized layer gradation reduced damage propagation.
[7]	3D printed concrete + self-healing cast concrete	Barrier systems	Cyclic flexural fatigue tests	Self-healing cast layer improved durability, reducing stiffness degradation by nearly 40% after repeated loading.

6.3. Numerical Simulations for Blast and Impact Resistance

Finite element modeling has been used extensively to simulate the dynamic response of protective concrete structures. Rigid body impact models, blast wave interaction (using ConWep or ALE techniques), and coupled fluid-structure interaction (FSI) simulations are common.

Employed LS-DYNA to model blast-loaded hybrid concrete walls, where a 3D printed front layer was bonded to a cast concrete backing. [33] The simulations, calibrated against experimental results, showed that layer configuration and interfacial bond strength significantly influenced peak deflection and residual capacity.

6.4. Applications in Military, Disaster Relief, and Infrastructure

The rapid and flexible construction capabilities of 3D printing make it highly suitable for time-sensitive protective applications. In military contexts, hybrid systems have been proposed for semi-permanent outposts, impact shields, and modular blast-resistant bunkers [12]. These systems can be printed on-site and reinforced with cast concrete to meet higher load demands [table 12].

In civil protection, 3D printed formworks combined with cast concrete infills have been used to create flood barriers, fire shields, and earthquake-resistant panels [22]. Such hybridization allows functional grading of strength, ductility, and insulation properties within a single structural element.

Table 12. Real-world and proposed use cases of protective hybrid concrete structures.

Structure Type	Location	Construction Type	Use Case	Threat Type	Status
Blast Wall	USAF Base	3D Printed + Cast	Explosion Shield	Blast Load	Operational
Shelter Dome	UAE	Fully 3D Printed	Civil Defense	Multi-hazard	Under testing

6.5. Opportunities and Challenges

While hybrid 3D printed–cast concrete systems hold strong promise for protective structures, several challenges remain:

1) Interface durability under cyclic impact and environmental exposure is still insufficiently understood.
2) Quality control in field-printed structures is difficult due to variability in printing parameters and environmental conditions.
3) Standardized testing protocols for impact and blast resistance of hybrid systems are limited.

Nevertheless, emerging techniques such as automated reinforcement placement, adaptive printing robotics, and digital twin-based performance monitoring offer promising directions for enhancing reliability and scalability [32].

In conclusion, the hybrid use of 3D printed and cast concrete in protective structures represents a synergy of speed, customization, and structural performance. While several experimental and numerical investigations have validated their effectiveness under blast and impact loads, future research should focus on field deployment, interface optimization, and standardized performance criteria to support widespread adoption in defense, disaster response, and resilient infrastructure systems.

7. Future Trends and Research Directions

As the construction industry shifts towards digitalization, automation, and sustainable practices, the combined use of 3D printed concrete (3DPC) and cast-in-place concrete in structural applications—particularly in protective structures—is poised to grow rapidly. However, to realize its full potential, several technical, material, and methodological challenges must be addressed [Table 15, Table 16]. This part outlines anticipated future developments and key research priorities, supported by emerging trends in material science, computational modeling, and field implementation.

7.1. Advanced Material Development and Sustainability

Future research will likely emphasize low-carbon printable mixes, including recycled aggregates, geopolymers, and ultra-high-performance concrete (UHPC) with tailored rheology for extrusion. These materials could enable stronger, lighter, and more environmentally responsible structures.

Table 13. *Emerging materials for 3DPC–cast concrete systems and their functional benefits.*

Material Type	Key Properties	Sustainability Potential	Application Area
Geopolymer Concrete	High fire resistance, low CO_2	Excellent	Protective shelters, barriers
Fiber-Reinforced UHPC	High tensile capacity, impact resistance	Moderate to High	Blast walls, impact shields
Recycled Aggregate Concrete	Variable strength, cost-effective	High	Temporary protective systems

Moreover, multi-material 3D printing is gaining attention, where gradient transitions from ductile to brittle phases (or vice versa) can be spatially programmed to improve energy dissipation and interfacial bonding. Integrating sustainable admixtures such as nanocellulose or bio-based polymers also presents a promising avenue for enhancing durability and ecological performance [Table 13].

7.2. Enhanced Interfacial Engineering

One of the central challenges remains the mechanical integrity of the 3DPC–cast concrete interface under variable load and environmental conditions. While studies have examined mechanical interlocking and surface roughness, future work must explore:

1) Smart interfaces with embedded sensors to track strain, humidity, and micro-cracking.
2) Functional coatings or primers applied to printed layers before casting to enhance chemical bonding.
3) Topology optimization of interfaces through AI-driven algorithms to improve anchorage and reduce failure risk.

7.3. Next-generation Computational Modeling

The coming decade is expected to witness the adoption of digital twin frameworks that fuse multi-physics simulations, machine learning (ML) models, and real-time field data to monitor and predict the long-term performance of hybrid concrete structures.

In parallel, researchers are beginning to use data-driven surrogate modeling to replace time-consuming finite element simulations, especially for rapid assessment under blast or impact loading scenarios. These approaches will be essential in validating protective structures for field deployment in disaster zones or military operations [Table 14].

Table 14. *Comparison of conventional FE methods vs. ML-based predictive models for hybrid concrete systems.*

Methodology	Accuracy	Computation Time	Data Requirement	Scalability
Traditional FEM	High	High	Moderate	Limited (case-specific)
ML Surrogate Models	Moderate–High	Low	High	High
Hybrid FE + ML	Very High	Medium	High	Medium–High

7.4. Field Applications and Robotic Integration

The shift from laboratory-scale to real-world applications requires advances in on-site robotic printing, automation of reinforcement placement, and integration of monitoring systems. Key directions include:

1) Autonomous mobile 3D printing units for field deployment in conflict zones and disaster-hit areas.
2) Real-time quality control systems, using embedded sensors and drones for surface inspection.
3) Integrated design-to-fabrication platforms, allowing engineers to modify structural parameters based on site conditions or structural monitoring feedback.

7.5. Policy, Standards, and Lifecycle Assessment

To support widespread adoption, there is an urgent need for standardization of test methods, design codes for hybrid structures, and lifecycle assessment (LCA) tools that consider construction, service, and decommissioning stages.

Government and defense agencies, in collaboration with academia, are expected to develop formal frameworks for certifying protective 3DPC–cast systems. These may include guidelines on bond strength thresholds, durability standards, and inspection protocols post-deployment.

Table 15. *Future Research Needs and Potential Research Directions.*

Research Focus Area	Description	Expected Impact
Interface Surface Optimization	Use of textured nozzles, automated brushing before casting	Increased bond strength and uniformity
Standardized Testing Methods	Unified protocols for slant shear, direct tension, and pull-off tests	Cross-study comparability
High-Fidelity 3D Interface Modeling	Incorporating mesostructure and porosity into digital twins	Realistic simulation and prediction
Sustainable Material Combinations	Use of recycled aggregates, geopolymer in print or cast layer	Eco-efficient hybrid structures
Field-Scale Implementation	Pilot projects in protective and military infrastructure	Real-world validation of hybrid performance

Table 16. *Future research directions and associated implementation challenges.*

Research Direction	Potential Impact	Current Barrier
Smart Interfaces & Coatings	Increased durability, adaptive response	Lack of field validation
AI-Powered Design Optimization	Performance efficiency	Model training and generalization
Lifecycle Sustainability Metrics	Informed material selection	Data scarcity and complexity
Robotic On-Site Integration	Rapid, modular construction	Technological and logistical gaps

In conclusion, the evolving landscape of 3D printed and cast concrete composites reveals a multitude of interdisciplinary research opportunities—from material science and computational modeling to field robotics and sustainability. As innovation in interfacial bonding, digital design, and protective applications continues to advance, hybrid systems are well-positioned to redefine how we design and construct resilient, high-performance structures in both civilian and military contexts.

8. Conclusion

This work presents a comprehensive examination of the mechanical bond behavior and composite action between 3D-printed and cast concrete, particularly in the context of protective concrete structures. By comparing their unique characteristics, it highlights how the fusion of 3D printing's design freedom and automation with cast concrete's reliability creates a complementary hybrid system. Key factors such as anisotropy, layer adhesion, surface texture, and curing time significantly affect interfacial bond strength. Experimental results underscore the importance of mechanical interlocking, though the lack of standardized testing methods remains a barrier to consistent comparative analysis.

Additionally, the review underscores the growing role of advanced numerical modeling—including finite element methods, cohesive zone models, and machine learning tools—in predicting and enhancing interface performance. The practical applications of this hybrid technique are promising, especially for rapid-deployment protective structures such as blast walls and military fortifications. The study calls for further research into sustainable materials, robotic fabrication, and smart interfaces, along with standardization efforts to support large-scale implementation. As interdisciplinary research and real-world projects advance, the integration of 3D-printed and cast concrete holds transformative potential for creating resilient, adaptive, and sustainable infrastructure.

Abbreviations

AI	Artificial Intelligence
FRPs	Fiber-reinforced Polymers
SHM	Structural Health Monitoring
UHPC	Ultra-high-performance Concrete
FEM	Finite Element Methods
3DCP	Three-dimensional Concrete Printing
DTs	Digital Twins
ML	Machine Learning
LCA	Life Cycle Assessment
GAs	Genetic Algorithms

Authors Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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