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Analytical Investigation of the Effect of 3d Printing Process Parameters on Anisotropic Mechanical Behaviour of Additively Constructed Concrete

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Abstract: This research identifies key challenges in additively constructed concrete, including the need for understanding the scalability of mechanical behaviour from small to large structures, addressing variability in material properties, and predicting failure mechanisms.
It highlights the need for improved finite element modelling for accurate 3DCP simulation, and further investigation into concrete foundation interactions and initial imperfections.
The study acknowledges difficulties in simulating complex shapes and calls for refinement of the numerical model for better predictive accuracy. It also emphasizes the need to understand long-term behaviour, durability, and the impact of the 3DCP process on microstructural morphology and mechanical properties. The influence of pores and time gaps between layers on the overall capacity of the specimen, and the development of a model considering different properties of 3D concrete material are also identified as areas for future research.

I. INTRODUCTION

A. General

Additive Constructed Concrete(3DCP) is a cutting-edge construction technique that utilizes digital fabrication processes for cement-based materials. It has gained significant traction since its inception in the 1990s, particularly due to advancements in mix design and printing technology over the past decade. This method eliminates the need for traditional formwork, thereby minimizing material wastage and enabling the construction of intricate structures with greater design flexibility. The architectural and structural applications of 3D-printed concrete span from building components and street furniture to pedestrian bridges and residential buildings. Its benefits include reduced waste, enhanced design freedom, faster construction times, customization options, potential cost savings, and improved sustainability.

As technology continues to progress, the scope for using 3D concrete printing in larger construction projects continues to expand. During 20th century, there were continual advancements in automating concrete processes. The idea of 3D printing came in 1980s, mainly for the materials like photopolymers and thermoplastics.

At early stage, 3D printing was primarily used in industries with great importance such as aerospace and biomedicine, due to its material costs. After some time, knowledge of 3D printing expanded to a level such that new additive manufacturing methods came into existence for different materials, including concrete.

The advent of 3D concrete printing (3DCP) has revolutionized the construction industry by enabling the layer-by-layer fabrication of concrete structures without the need for traditional molds. This innovative approach offers numerous advantages over conventional casting methods, including enhanced design flexibility, accelerated construction timelines, and reduced labour requirements on-site. However, the mechanical characteristics of 3D printed concrete materials present unique challenges that necessitate thorough investigation and understanding.

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Figure 1. 3DCP in Processing

While traditional concrete behaviour has been extensively studied, the specific properties of 3D printed concrete demand further exploration. In particular, the concept of "buildability," which refers to a material's ability to maintain stability and retain its shape immediately after extrusion, is crucial in 3DCP due to the absence of supportive molds. Achieving adequate buildability requires materials with sufficient yield stress and structuration rates, which dictate the speed at which the material gains strength. Although analytical models and empirical tests have been developed to estimate maximum printable heights and assess material buildability, accurately predicting the performance of 3DCP structures remains a complex task. To address these challenges, researchers have increasingly turned to numerical modelling and simulations to simulate the 3DCP process and predict the mechanical behaviour of printed concrete. These computational approaches offer a cost-effective and time-efficient alternative to experimental trial and error. However, the accuracy of numerical models relies heavily on selecting appropriate material models to characterize the early-stage mechanical properties of 3D printed concrete. Several studies have explored various numerical modelling techniques and material models to simulate the 3DCP process and predict the behaviour of printed concrete structures. For instance, Di Carlo employed the Drucker–Prager yield criterion and time dependent material properties, while Xiao et al. utilized the CDP model and the traction separation law. Despite these efforts, a comprehensive understanding of the most suitable constitutive models for 3D printed concrete remains elusive. In this context, the present study aims to contribute to the advancement of numerical modelling in 3DCP by addressing key technical challenges. Specifically, we focus on a numerical model that considers the diverse compressive and tensile properties of 3D concrete printing materials. Our research endeavours to improve the accuracy of numerical simulations by investigating different material models and modelling techniques. The remainder of this thesis introduces the finite element modelling of 3DCP using a novel tracing element approach. Later, conducts finite element analysis on typical 3D printed concrete structures, including validation of models and failure analysis. Then, presents a theoretical study on various constitutive models for characterizing the mechanical behaviours of fresh concrete used in 3DCP. Through these efforts, we seek to enhance the understanding and application of numerical modelling in 3DCP and contribute to the development of more reliable and efficient construction techniques.[1], [2], [3] In 3D Concrete Printing (3DCP) process, the printed object must support itself from the moment of deposition onward, as there is no formwork involved. This requires that 3D printed cementitious materials exhibit good "buildability", which refers to their ability to maintain geometric stability while subjected to increasing gravitational loads during the layer-by layer printing process.[4], [5] To define the proper buildability, numerical modelling and simulations are indeed crucial in determining the buildability of 3D printable materials.

These methods can simulate the 3D Concrete Printing (3DCP) processes, which can help avoid costly and time-consuming trials and tests. The concrete used in 3DCP has specific properties, such as compressive and tensile strengths, which are typically determined through lab testing or standard values. A numerical model is made to simulate the printing process, using the Finite Element Method (FEM) to handle large deformations and nonlinearity. This model is then validated by comparing its results with experimental data, providing valuable insights that can help optimize the 3DCP process. As 3DCP continues to gain traction in the construction industry, further research is being conducted to explore its potential and practicality. The study addresses the challenges related to the sustainability and productivity of the construction industry and aims to establish a relation between the process parameters and the printed product to avoid unreliability and failure.

B. Numerical Methods

In the realm of 3D Concrete Printing (3DCP) modelling, several numerical methods are employed. The Particle Finite Element Method (PFEM) is used to simulate the printing process, taking into account the homogeneous fluid assumption and handling large deformations and nonlinearity. On the other hand, Finite Element Analysis (FEA) is the practical utilization of the Finite Element Method (FEM) to address engineering challenges. It entails the use of FEM software to construct a digital representation of a physical entity, impose boundary conditions and loads, and subsequently examine the system's reaction. FEA is widely employed in engineering design and evaluation to anticipate the behaviour of structures and systems under diverse circumstances.

II. NEED AND SCOPE OF STUDY

The development of numerical models, such as the finite element method and concrete damage plasticity model available in Abaqus, is vital for analysing 3D concrete materials. These models consider the distinct tensile and compressive properties of concrete, enabling a comprehensive understanding of its behaviour under various conditions. They facilitate the simulation of failure processes, prediction of material responses, and enhancement of structural analysis. Furthermore, they provide valuable insights for improving material design. Overall, these models are indispensable tools in the field of concrete material study, offering a detailed understanding of the failure processes of concrete under tensile and compressive loads.

III. LITERATURE REVIEW

Some of the relevant literatures which are needful and relevant to the topic are described below:

Zhao et al. 2022 [6] discussed the advancements and potential of concrete 3D printing technology in the construction industry. It highlights the limitations of traditional construction methods, such as environmental concerns and low accuracy, and presents concrete 3D printing as a solution that offers environmental benefits, higher precision, and the ability to construct complex shapes. The study reviews the current state of concrete 3D printing, including equipment, materials, defect control, and application scenarios, and provides a forecast for its future development. The technology is seen as a promising step towards more sustainable and innovative construction practices.

Nematollahi et al. 2017 [7] examined the innovative strides in 3D concrete printing (3DCP) and its potential to revolutionize the construction industry. It outlines the benefits of 3DCP, such as cost reduction, waste minimization, and enhanced design flexibility. The paper reviews various 3DCP methods, with a focus on extrusion and powder-based techniques, and introduces a new approach for creating geopolymer-based materials for 3D printing. It also discusses the challenges faced by traditional construction methods, including high costs, environmental impact, and design limitations, suggesting that 3DCP could offer a more efficient, safer, and environmentally friendly alternative. The literature review within the paper provides a foundation for understanding the current advancements and future possibilities of 3DCP in building better structures.

Pal et al. 2024 [8] investigates the influence of 3D printing parameters on the structural integrity of concrete. The authors use a finite-element model to simulate the behaviour of 3D printed concrete beams under load, focusing on the bond strength between layers, stiffness, and the presence of voids. They find that optimal tensile bond strength is crucial for achieving maximum load capacity, while higher bond stiffness can lead to early damage and reduced load capacity. The study also examines how the displacement after peak load and the initial stiffness of the bond influences the mechanical behaviour, finding that greater bond fracture energy enhances ductility and load capacity, while higher initial stiffness may lead to premature damage. Additionally, a better shear to tensile bond strength ratio correlates with increased load capacity. These insights, while based on specific test conditions, offer a framework for estimating the load-bearing capabilities of 3D printed concrete, underscoring the importance of parameter optimization in additive manufacturing.

Buswell et al. 2018 [9] examined the advancements and challenges in 3D concrete printing (3DCP) technology. It highlights the technology's potential to transform the construction industry by enabling the creation of complex structures without traditional molds. The paper identifies key technical issues, such as the need to understand the interplay between the material's properties in both fresh and hardened states and their impact on the printed structure's geometry. It also points out the necessity for precise control over the extrusion process to ensure the accuracy of the printed forms. The authors propose a research matrix tailored to different construction applications, providing a structured approach for future investigations in 3DCP. They emphasize the significance of optimizing material properties and printing parameters to achieve structural integrity and desired aesthetics. The paper calls for a collaborative, multidisciplinary research effort, combining knowledge from materials science, engineering, and architecture, to push the boundaries of 3DCP.In essence, this paper serves as a guide for future research in 3DCP, outlining the current state of the technology, its potential applications, and the necessary steps for its progression. It is a vital resource for those looking to contribute to the evolution of 3D printing in the construction sector.

Xiao et al. 2021 [10] investigates the directional strength and deformation of 3D printed concrete. The literature review acknowledges the advancements in 3D printing but points out the need for more research on the anisotropic characteristics due to the layering process. The paper introduces a finite element model that simulates the bond between layers, validated against experimental data. This model assesses the impact of printing parameters on mechanical properties. The research finds that interlayer shear affects compressive strength, while tensile strength influences flexural capacity. The anisotropic behaviour varies with the direction of load application, affecting design and construction of 3D printed structures. This work is foundational for future research addressing the anisotropic challenges in 3D printed concrete.

Xiao et al. 2013 [11] discusses the impact of Interfacial Transition Zones (ITZs) on the stress-strain behaviour of Modeled Recycled Aggregate Concrete (MRAC). It highlights the importance of ITZs and new mortar matrix in determining MRAC's mechanical properties under uniaxial compression and tension2. The study uses nanoindentation tests and plastic-damage constitutive models for numerical analysis, validated by experimental results. It reveals that the mechanical properties of the new mortar matrix and the relative properties between ITZs and mortar matrices significantly influence MRAC's overall stress-strain relationship and failure patterns. The paper also explores the complexities of RAC's microstructure, including the presence of old and new ITZs, and their effect on RAC's lower strength compared to conventional concrete. The research contributes to a better understanding of RAC's mechanical behaviour, which is crucial for its application in structural and non-structural elements. The findings suggest that optimizing ITZs and mortar matrix properties could enhance RAC's performance, making it a more viable construction material. The study's insights into the micromechanical behaviour of concrete through advanced simulation techniques offer valuable guidance for future concrete engineering and research.

Zareiyan et al. 2017 [12] explores the impact of interlocking on the strength and adhesion between layers in 3D printed concrete structures. It presents a concrete mixture suitable for the Contour Crafting (CC) extrusion system and examines various interlock configurations through experimental methods. The findings reveal that interlocking significantly enhances bond strength, with an average increase of 26% as per splitting tests. The study delves into the importance of layer bonding in 3D printed concrete, highlighting that while some structures achieve bond strengths comparable to monolithic segments, others show vulnerability at the bond interfaces. The research contributes to a deeper understanding of how interlocking affects the homogeneity and sustainability of 3D printed concrete structures. It also discusses the integration of technologies like Building Information Modelling (BIM) and sensing automation to improve construction efficiency, energy use, and occupant satisfaction. The paper underscores the challenges in developing techniques that ensure strong layer adhesion for a homogeneous structure and suggests that topological interlocking could be a solution. This design principle, which relies on geometrical constraints without binders or connectors, offers advantages such as resistance to crack propagation and high energy absorption. The study's primary goal is to assess the influence of interlocking on the structural integrity of CC structures, aiming to enhance the bond interface of cementitious materials used in 3D printing.

Sanjayan et al. 2018 [13] focuses on the weak inter-layer strength of printed concrete, a limitation when compared to traditional cast-in-mold concrete. It examines the effects of print-time intervals on inter-layer strength, as well as compressive and flexural strengths in different directions. The research found that a 10 and 30-minute delay in print-time intervals resulted in comparable inter-layer strengths, which were higher than those with a 20-minute delay. The study suggests that surface moisture content at the interface of layers, influenced by bleeding and evaporation rates, is a key factor affecting inter-layer strength. The orthotropic nature of 3DCP was observed, with directional differences in compressive and flexural strengths. The article concludes that optimizing the delay time between layers is crucial for achieving adequate green strength and bond strength, which are essential for the structural integrity and economic feasibility of 3DCP in construction. The study fills a knowledge gap by linking delay time and surface moisture content to the mechanical properties of 3D printed concrete.

Panda et al. 2018[14] formulated a new geopolymer mortar using fly ash and investigated how various printing parameters, such as the time gap between layers, nozzle speed, and nozzle standoff distance, affect the bond strength. They used a four-axis automated gantry system for printing and found that bond strength is influenced by the state of the interface material between layers, which is determined by the material's strength development rate and the printing parameters. The article highlights the importance of understanding the bond mechanism to improve the structural capacity of construction joints in concrete structures. It also emphasizes the environmental benefits of using geopolymer, which has a lower carbon footprint compared to ordinary Portland Cement (OPC). The study contributes to the field of 3D concrete printing (3DCP) by providing insights into the factors that affect the interfacial bond strength of printed geopolymer mortar, thereby aiding in the advancement of sustainable construction technologies.

Tay et al. 2019[15] examined the influence of time intervals between layer depositions in 3D-printed concrete structures. It focuses on how these intervals affect the bond strength at the interfaces, which is crucial for the structural integrity of the final construction. The study employs rheological measurements to analyze the material's deformation and flow behaviour, which is essential for understanding the structural build up during the printing process. The research findings indicate that the tensile strength of the printed concrete is closely related to the material's modulus in the initial layer, emphasizing the importance of managing the time gap in the printing process to optimize the bond strength and ensure the stability of 3D-printed structures. This study contributes to the field of 3DCP by providing insights into the factors that affect interfacial bond strength, aiding in the advancement of sustainable construction technologies.

Chen et al. 2023 [16] discussed the development of a 'one-part' geopolymer concrete enhanced with steel fiber for 3D concrete printing (3DCP), aiming to improve its tensile strength, ductility, and toughness. The study systematically examines the impact of steel fiber content and aspect ratio on the mechanical properties of the material, including compressive and flexural strength, splitting tensile strength, uniaxial tensile strength, and bending toughness. X-ray computed tomography (X-CT) testing is used to analyze fiber distribution in the printed samples. The results show significant improvements in mechanical properties, with flexural strength increasing by 282% to 26.1 MPa and compressive strength reaching 104.5 MPa. The material demonstrates high tensile ductility, appreciable bending toughness, and strain-hardening behaviour, outperforming other steel fiber materials in 3D printing and existing geopolymer fiber reinforcements. The 'one-part' geopolymer concrete's sustainability is highlighted by its lower CO2 emissions compared to Ordinary Portland Cement (OPC), making it a promising alternative for 3D printing applications requiring high tensile strength. The paper also addresses the challenges of reinforcing structures created through extrusion-based 3D printing technology and proposes the use of fiber reinforcement to enhance the material's performance. The research contributes to the advancement of 3DPC technology by offering a new material that combines environmental benefits with improved mechanical properties, potentially revolutionizing the construction industry.

Heever et al. 2022 [17] discussed the impact of porosity on the mechanical properties of 3D printed concrete. It highlights that 3D printed elements show anisotropic behaviour and weaker mechanical characteristics compared to mold-cast counterparts due to porous interfacial joints. The study investigates the correlation between porosity metrics—like defect content, void topology, and interconnectivity—and the mechanical performance of fiber-reinforced printable concrete. X-ray computed tomography is used to quantitatively analyze these porosity metrices and relate them to the elasticity, compressive strength, and fracture patterns of both 3D printed and mold-cast specimens. The findings suggest that higher porosity and altered void attributes in 3D printed samples lead to reduced elastic modulus and compressive capacity, which are influenced by porosity content, loading direction, stress concentrations, and deformability of the composite material potential solutions to improve the anisotropic mechanical response of 3D printed concrete are proposed based on these insights.

Babafemi et al. 2021 [18] provides a comprehensive review of interlayer bond strength in 3D concrete printing (3DCP), emphasizing its critical role in the mechanical and durability properties of printed structures. It discusses the influence of various factors such as material design, process parameters, and printing environment on bond strength. The paper also examines testing methods for bond strength measurement, including mechanical and microstructure characterization, and explores strategies for enhancing bond strength through mechanical interlocking and surface/interface reactions. Additionally, it highlights the need for standardized testing and specimen preparation methods to ensure consistent and reliable results in 3DCP research.

Wolfs et al. 2018[19] discuss the development of numerical model to analyze the mechanical behaviour of 3D printed concrete shortly after deposition between 0 to 90 minutes, focusing on the time-dependent development of its properties.

An experimental program was conducted to determine the necessary material properties through compression and shear tests, revealing that certain properties like Young's modulus and cohesion increase linearly with the age of the fresh concrete. The model was validated against actual printing experiments, showing qualitative agreement but highlighting areas for quantitative improvement. The study emphasizes the importance of understanding the mechanical behaviour during the printing process, as it affects both the printability and the final product's quality. It also notes the challenges in developing a modelling method for 3D concrete printing, such as selecting a suitable material failure model and adapting geotechnical test methods for concrete. The research contributes to the digitalization of construction processes and the advancement of additive manufacturing techniques in the industry.

Ooms et al. 2021 [20] presents a Parametric Modelling Strategy for simulating 3D concrete printing (3DCP) with complex geometries. It introduces a tool that automates the creation of finite element models, enabling the simulation of structural behaviour during printing. This aids in optimizing the printing process, reducing material waste, and improving efficiency. The tool's effectiveness is validated through case studies comparing experimental and numerical results from literature. The research highlights 3DCP's advantages, such as design freedom and cost savings, and addresses challenges like material properties and buildability. Ultimately, the tool contributes to advancing 3DCP technology by facilitating the simulation of intricate designs without extensive manual modelling.

Lee et al. n.d. [21] introduces a plastic-damage model tailored for concrete structures under cyclic loads, integrating damage mechanics with fracture-energy concepts to simulate crack initiation and propagation. It employs dual damage variables to represent tensile and compressive damages and a yield function with multiple hardening variables. The model separates uniaxial strength functions into stress and stiffness degradation components, facilitating calibration with experimental data. It also features a scalar degradation model for elastic stiffness, accounting for damage effects and recovery. Demonstrated through numerical examples, the model adeptly captures concrete's stiffness degradation and dilatancy under cyclic loading, offering a macroscopic perspective on microcrack development and a robust framework for predicting the durability of concrete structures.

Hafezolghorani et al. 2017 [22] introduces a Simplified Damage Plasticity Model (SDPM) for concrete, designed to streamline the complex Concrete Damage Plasticity (CDP) model for easier application in structural engineering. The SDPM, which is presented in tabular form for various concrete grades, simplifies the simulation of unconfined concrete behaviour, focusing on its primary failure modes: compression crushing and tension cracking. The model is integrated into finite element analysis, with a case study on a prestressed beam demonstrating its effectiveness and correlation with empirical data. This approach offers a practical alternative to the CDP model, reducing computational intensity and facilitating routine structural analysis.

Chen et al. 2018 [23] investigates the meso-scale mechanical behaviour of concrete under uniaxial tensile and compressive loadings. The study employs a numerical concrete modelling approach to construct meso-scale models that incorporate the random distribution and geometrical shape of aggregates, as well as the interfacial transition zone (ITZ). The research examines the sensitivity of the meshing approach and the influence of the ITZ on the macro stress-strain relationship, damage evolution, and final failure pattern of concrete. Results show that the meso-scale structure of concrete distinctly affects the nonlinear and stochastic characteristics of macro stress-strain curves and failure patterns under different loading conditions. While the geometrical parameters of aggregates have a limited effect on macroscopic tensile strength, they significantly impact the post-tension segment and the compressive macro stress-strain curve. Additionally, the presence of ITZ notably influences the tensile and compressive strength of concrete. The study also compares the statistical characteristics of macro stress-strain curves from multi scale simulation with experimental studies, validating the meso-scale simulation approach.

IV. GAPS IN LITERATURE REVIEW

1) Some points are lacking in understanding the scalability of mechanical behaviour from 3D printed beams to full-scale structures. More investigations on studies are needed to ensure that the positive results seen in beam experiments can be applied to the construction of larger buildings and complex architectural forms.
2) It might not address the variability in material properties that can occur due to different sources of raw materials or changes in the manufacturing process.
3) The failure mechanisms of 3D printed concrete structures are not well understood and are challenging and difficult to predict.
4) Existing technical issues in finite element (FE) modelling need addressing for accurate simulation of 3D concrete printing (3DCP), including initial deformations and failure identification.
5) The modelling methods for concrete foundation interactions and initial imperfections are varied and require further investigation.
6) There are some difficulties need to be resolved in simulating 3DCP for complex shapes due to issues like pumpability, extrudability, and buildability.
7) The study focused on the mechanical properties of fresh concrete shortly after deposition, but there is a gap in understanding behaviour and durability of 3D printed concrete structures. the long-term.
8) There is a need to understand how the 3DCP process impacts microstructural morphology and, consequently, the mechanical properties.
9) There is a lack of study to find out the influence of pores and time gap between adhesively bonded layers on the overall capacity of the printed concrete specimen. Previous studies have not fully explored how porosity, especially at the interfacial joints between filament layers, affects the mechanical characteristics of 3DCP.

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V. RESEARCH METHODOLOGY

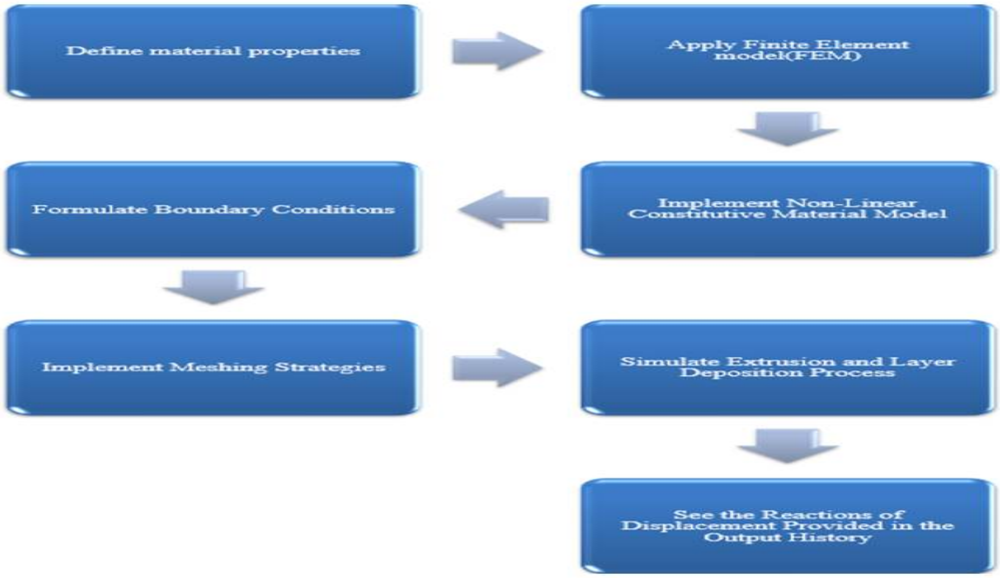

Figure 2. Flow Chart for Methodology

VI. EXPECTED OUTCOMES

1) An approach to understand the relations between the printing process, the process parameters, and the properties of the printed product. It paves the way for the use of numerical modelling tools for the optimization of materials and processes in the field of 3D Concrete Printing.
2) The insights gained from the numerical modelling can lead to the optimization of materials and processes in the field of 3D Concrete Printing.
3) It offers a comprehensive understanding of the relationship between the printing process, process parameters, and the properties of the printed product.

VII. RESULTS AND DISCUSSION

By varying printing parameters in simulations like tensile bond strength, stiffness and plastic displacement, various results have been plotted to see the relatable differences and to come up with appropriate conclusion.

So, different models are analysed using same boundary condition of bottom fixed and giving displacement from upper surface of the cube by generating a reference point so that reaction could be analysed easily.

Interaction in chosen between surface as Cohesive and damage in which various normal and shear parameters are used with the values and varying a parameter at one time by fixing all other parameters, results are analysed.

So, particularly in every case of variation, the results are seemed to be same. For the results to be precise and short, only bond strength variation is analysed when it is taken as 1MPa and 2MPa in shear direction i.e. Shear bond strength

Results have been seen of different models i.e. having a layer of 15*30 and with varying pore size of 1mm, 2mm and 3mm so that compressive strength could be seen in every case of practicality.

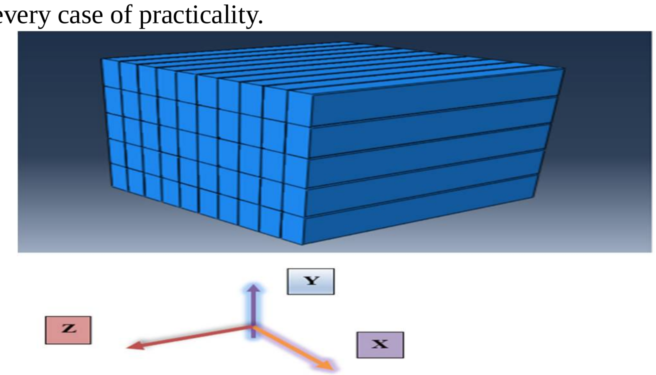

Figure 1. Directions in which loading is applied to the model

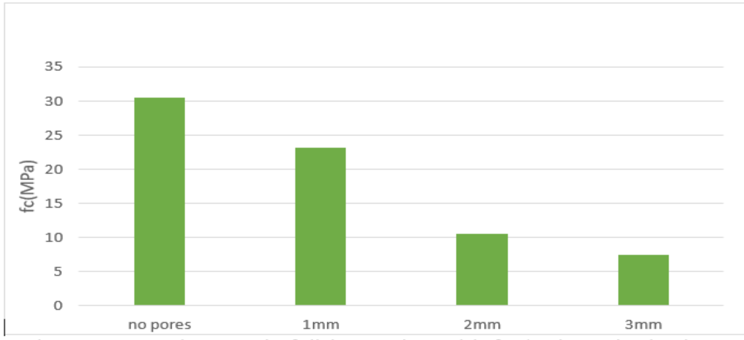

Figure 3. Compressive Strength of all the pore size model of 15*30 layer when bond strength=1MPa and loading is given in Y direction

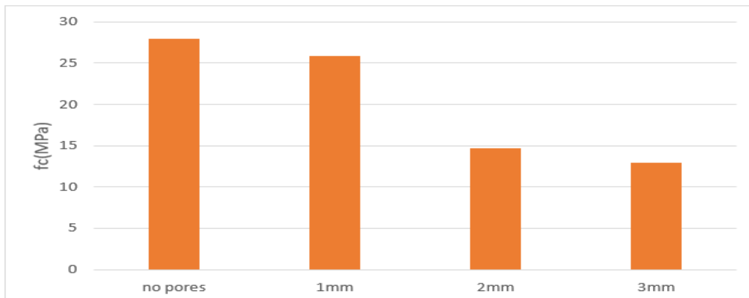

Figure 4. Compressive Strength of all the pore size model of 15*30 layer when bond strength=1MPa and loading is given in X direction

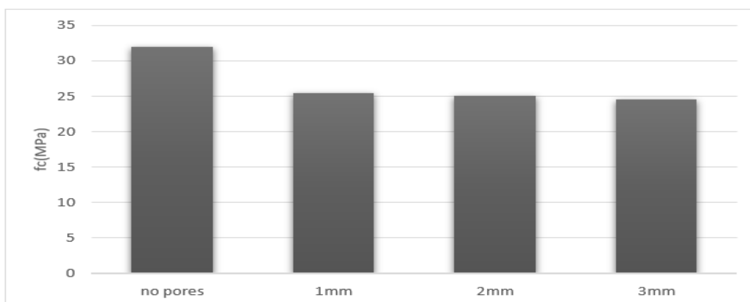

Figure 5. Compressive strength of all pore size models when bond strength=1MPa and loading is given in Z direction of the model.

- After near about 150 simulations, the insights gained from the analysis and results are like that there is not such effect of variation of bond strength, stiffness, plastic displacement.
- Effect of pore size variation in the model can be seen effectively in the strength parameter.
- Also, the size of layer matters in the strength output parameter and convergence time. Smaller the size greater the time of convergence.
- In the different direction of loading of same model, it can be seen that there is significant difference in strength output which can be considered.

VIII. CONCLUSION

A. *Pore Characteristics*

The presence of pores significantly influences the mechanical behaviour of additively constructed concrete. Pores can act as stress concentrators, reducing overall strength and durability.

B. *Anisotropic Behaviour*

The orientation of printed layers (printing direction) plays a crucial role in anisotropic mechanical properties. For instance:

1) *Longitudinal Direction:* Layers parallel to the loading direction exhibit higher tensile strength due to better interlayer bonding.
2) *Transverse Direction:* Layers perpendicular to the loading direction may have reduced strength due to weaker interlayer connections.

C. Pore-Induced Anisotropy

Pores affect anisotropy by altering stress transfer pathways. In the longitudinal direction, pores may hinder crack propagation, while in the transverse direction, they can exacerbate it.

IX. FUTURE SCOPE

1) *Optimization of Printing Parameters:* Further research can explore optimal combinations of printing parameters to enhance mechanical performance while minimizing material usage.
2) *Large-Scale Reinforced Structures:* Investigate additive construction challenges for large-scale reinforced concrete structures, addressing accuracy, performance, and material properties.
3) *Anisotropic Behaviour:* Study anisotropic effects in detail, considering layer-by-layer printing and its impact on overall strength and structural integrity.

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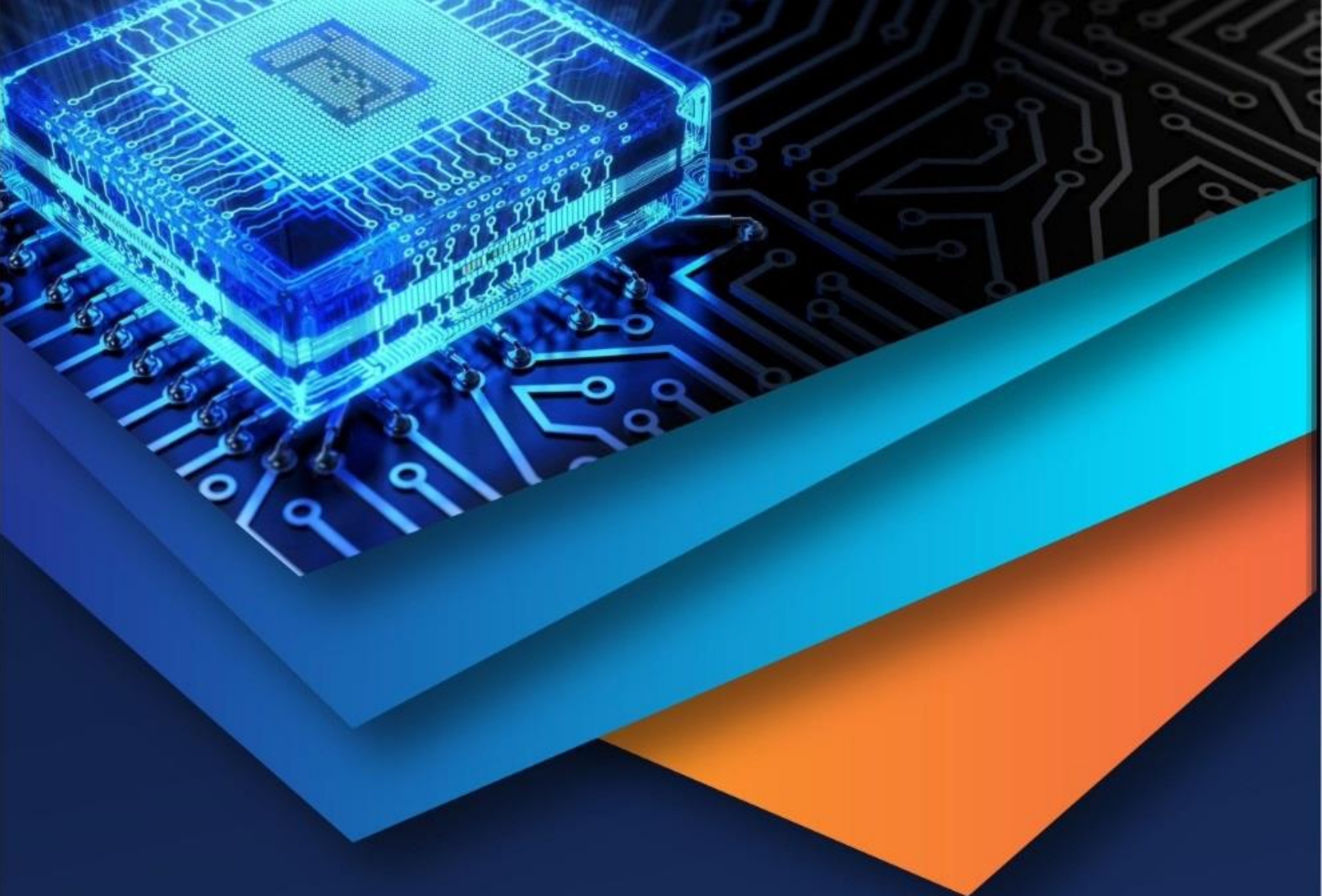

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