Experimental set-up for shear and interlayer bonding in a 3D printed concrete framework

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Abstract. Three-dimensional concrete printing (3DCP) represents a revolutionary advancement in the construction industry, fundamentally reshaping traditional construction methods. This cutting-edge technology not only holds the promise of enabling the construction of architecturally optimized structures but also addresses crucial issues including material conservation and streamlined construction processes. However, the complex nature of 3DCP poses challenges in order to fully unlock its potential. The primary focus is on scrutinizing the bond strength between consecutively deposited layers, a critical factor influencing structural integrity and the overall quality of printed structures. The strength of this bond depends on several factors, including surface moisture, temperature, surface roughness, and the times of the printing process as related to the material strength development, affecting the formation of cold joints and collectively governing structural quality and reliability. Existing literature has explored various methodologies to improve this bonding parameter, such as wire mesh, U-nails, steel reinforcement, and fibers. This study introduces an inventive approach utilizing stainless steel nails for establishing interlayer connections. In the context of this research project, the primary objective was to evaluate the enhancement to bond strength between successive layers of fresh concrete in the additive manufacturing process. A specialized testing configuration, consisting of a shear box equipped with two “chambers”, was employed. In this setup, the initial layer underwent 3D printing in the lower chamber, followed by the deposition of the second layer in the upper chamber, accompanied by the positioning of reinforcement nails. This approach facilitated a meticulous assessment of bond quality between these layers. The methodology enabled the identification of variations in bond strength and allowed for time-dependent tests to monitor the initiation and progression of cold joint formation, if any. Notably, different deposition times for the second layer in the upper chamber were explored, ranging from one minute after the first layer to as long as 60 minutes later, following the insertion of reinforcements. This research has provided valuable insights into the pivotal domain of interlayer bonding in 3DCP, illustrating how the integration of specific reinforcements throughout the structure can enhance this parameter and how it evolves over time.

Keywords: 3D printing; Intralayer bond strength; Steel nails, Reinforcement.

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1 Introduction

The digitization of the construction industry is experiencing rapid and significant expansion thanks to the adoption of processes and technologies leveraging the innovations of additive manufacturing techniques. This enables the automated creation, design, and realization of advanced structures and specific prefabricated elements. In this context, 3D printing technology plays a crucial role [2][9]. However, the entire realization process is intricate as it consists of several phases including mixing, pumping, extrusion, and layer-by-layer deposition, with the lower layer having to support the weight of the upper layers. This process is often described solely through the study of material rheology, an important parameter that does not fully account for the complex procedure.

It is essential, therefore, to characterize and understand the evolution over time of the bond between the various layers, a primary aspect in the constructability phase, while seeking to define the formation of cold joints and the instability of such bond. To address this challenge, the use of an innovative shear box equipped with two chambers specifically designed for this field of application is proposed in this paper. In this configuration, the initial layer is printed in the lower chamber, followed by the deposition of the second layer in the upper chamber. This approach facilitates the accurate assessment of the bond quality between these layers, allowing for the identification of variations in shear strength and enabling time-dependent tests to monitor the onset and progression of cold joint formation. This methodology can be further exploited to characterize the effects that reinforcements, particularly for enhancing interlayer bonding, can have in the fresh, plastic, and hardened states. Currently, ensuring perfect bonding between reinforcements and the cementitious matrix is a central concern, especially when reinforcements are installed after the extrusion of 3D printed concrete [1][3]. As a matter of fact, there is a wide range of reinforcements specifically designed to increase the bond between the various layers, including steel nails, widely used for their versatility and ability to be adapted, angled, and densely arranged according to specific structural and architectural requirements also in other domains of building and structural engineering.

This article illustrates the validation and in-depth study of an experimental methodology for measuring and defining the evolution of the aforementioned property of a 3D printable cementitious mixture in the early stages with the addition of "through-layer" nail steel reinforcements.

2 Methodology

The experimental program outlined in this document involves conducting shear tests on a 3D printable cementitious composite. These tests aim to characterize the material and evaluate the impact of shear reinforcements by varying the time intervals from 10 to 60 minutes to observe the temporal evolution of this property. The tests were carried out using chambers fabricated from PLA through additive manufacturing techniques, consisting of a stationary lower chamber and a sliding upper chamber aimed

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at highlighting the “shear” interaction between the two layers of concrete repeatedly deposited in the moulds. The relative movement of the chambers is governed by an actuator with continuous screw motion, while a 2.5 kg load cell measures the shear resistance of the cutting area. Additionally, a variable linear displacement transducer (LVDT) was employed to measure the displacement (Fig. 1). These tools enabled the acquisition of stress-displacement curves representative of the interlayer bond behaviour, which will be discussed further in subsequent sections.

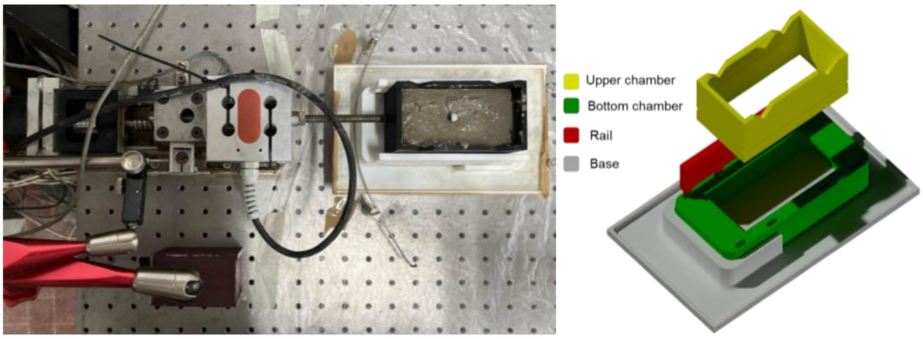

Fig. 1. Shear test set-up with a diagram showing the arrangement of the chamber.

In the selected methodology, the friction between the two chambers of the shear box was taken into account. To achieve this, a shear test was conducted without concrete, and the friction value obtained was then subtracted from the data recorded during the actual test to avoid overestimating the actual bond resistance of the material.

2.1 Mix-design

To ensure the reliability of the methodology, three different mix formulations previously examined in prior research [4][8] were considered. These formulations were selected primarily based on their suitability for 3D printing applications and, secondarily, on the availability of comprehensive rheological data, primarily the yield stress τ_0, obtained through rheometer tests. For this characterization methodology, only the results of one of the studied compounds, characterized by moderate strength (Table 1), are reported and discussed.

Table 1. Table captions should be placed above the tables.

	Cem I (%)	Agg. Max size (mm)	w/c	a/c
Mix A	100	2.00	0.4	1.3
Time (min)	15	35	55	75
SYS (Pa)	300	470	640	810

where w/c is the water-to-cement ratio and a/c is the aggregates-to-cement ratio (-).

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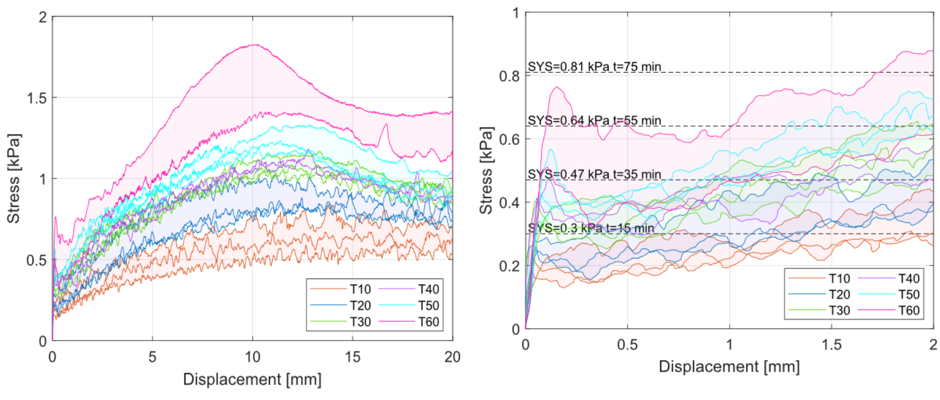
3 Results

To evaluate the properties of the selected concrete, two distinct types of tests were conducted. The first aimed to determine the effectiveness of the shear test in assessing the material's shear strength and its evolution over time [5][6][7]. During this phase, the concrete was poured simultaneously into the lower and upper chambers. The shear test was performed at 10-minute intervals, starting from a curing time of 10 minutes up to 60 minutes (from T10 to T60), always measured from the first contact of the cement with water during the cementitious composite mixing. The second type of test focused on analysing the bond between the various layers in the presence of steel reinforcements. However, the study of the cold joint will be the subject of future work.

3.1 Prediction of the Static Yield Strength

The initial step involved using the shear box as a method to evaluate the bond between different layers and determine the Static Yield Strength (SYS) of Mix A [4]. Test execution time was calculated from the start of liquid and powder mixing. During testing, the shear response of the investigated (yielding the static yield strength value) was assessed through a 20 mm induced shear displacement. Test interpretation could be conducted in terms of both "small displacements" and "large displacements," providing varied insights. As shown in Fig. 2a, a hardening trend was observed up to 10 mm, followed by subsequent softening. This curve reflects the overall resistance to sliding across the "shear ligament" area and, consequently, the resistance and bond between the two layers cast in the test setup.



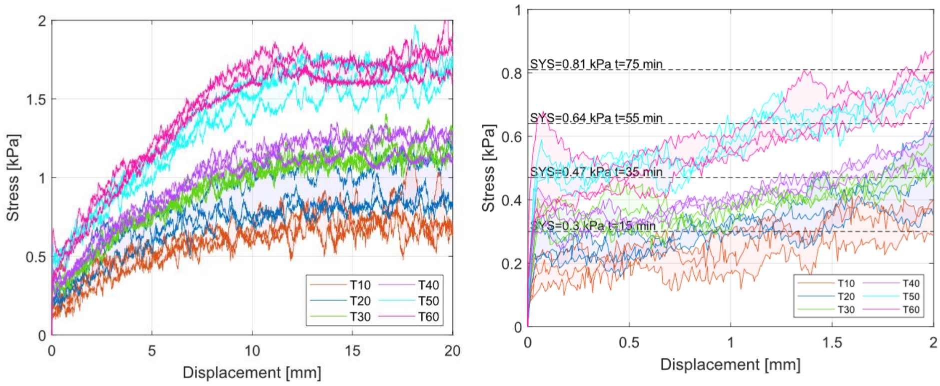
(a) (b)

Fig. 2. Shear test for Mix A, with different timings. (a) 20 mm displacement. (b) 2 mm displacement.

Alternatively, upon examining Fig. 2b, an "early" peak associated with the initial rupture of the material and shearing area was observed, indicating the initiation of concrete flow. This peak represents the maximum static resistance, signifying the point at which concrete begins to flow as the shear stress exceeds the interparticle strength. The test accurately identifies this rheological property, as evidenced by the peak recorded during the 50-minute test, which aligns with the stress values obtained from the rheometer test conducted at 35 and 55 minutes (dashed black lines), thus confirming the test's consistency over time. This precision was similarly observed across the other time intervals of the shear tests. Lastly, the methodology adeptly captures and discerns the structuring of the concrete over time.

3.2 Contribution of the reinforcement

To assess the effectiveness of steel reinforcement in improving interlayer bond in fresh concrete, a vertical steel nail reinforcement was placed at the centre of the shear area after filling the chambers with the cementitious material. Fig. 3 illustrates the results obtained from repeating three tests for each time interval (10, 20, 30, 50, 60 minutes). Despite a slight increase in scattering attributed to the change in the load cell, the data quality remains robust. Tests conducted with reinforcement show less variability compared to conventional ones, thereby enhancing the reliability of the test.



(a) (b)

Fig. 3. Shear test for Mix A, with steel reinforcement at different timings. (a) 20 mm displacement. (b) 2 mm displacement.

In this specific instance, the tested concrete remains in its plastic phase, as evidenced by images showing sliding motion indicative of failure due to refilling (Fig. 4). This collapse mechanism, akin to what's observed in wood connections, involves the concrete undergoing some kind of bearing failure upon contact with the nail, without any deformation in the much stiffer reinforcement.

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Fig. 4. Concrete refilling

3.3 Comparison

In the comparative analysis of “shear” strength tests, both with and without reinforcement, a meticulous examination was conducted on the results obtained from the 60-minute test (Fig.5).

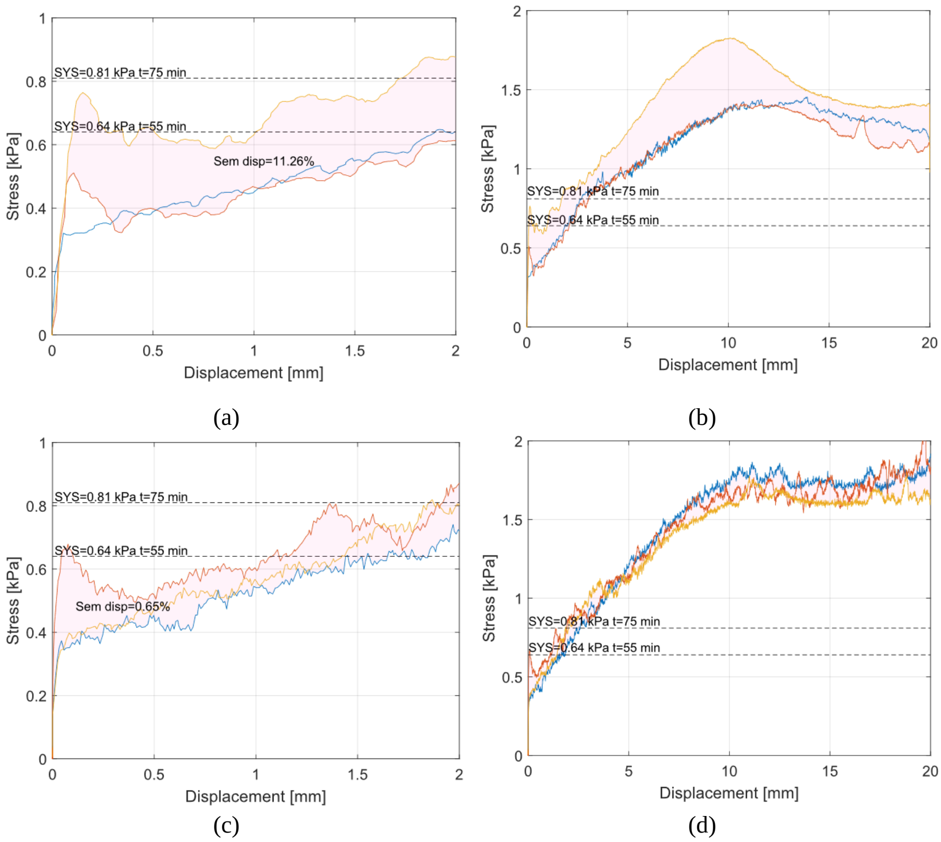

Fig. 5. Comparison between the shear test conducted at 60 minutes without reinforcement (a), (b), and the test with steel reinforcements (c), (d).

During the shear test, within the post-peak zone of up to 2 mm, a notable reduction in average deviation is observed due to the presence of nails. Furthermore, there is an approximate 10% decrease in the value of the "early" peak stress within the shear area, attributed to the disturbance of the nail, which can be pronounced due to its "post-insertion" when concrete is in its very early ages. On the other hand, of particular interest is the behaviour observed for displacements exceeding 10 mm. In this stage, a transition occurs from softening (without reinforcement) to plastic behaviour in the shear strength, thanks to the positive influence of reinforcement.

These observations, applicable to the 60-minute test point, can be extrapolated to other time intervals (Fig.6). The introduction of steel reinforcements leads to a decrease in the initial peak resistance during shear testing for small displacements, as previously mentioned. However, this trend reverses when considering larger displacements, resulting in an increase in the maximum peak resistance. Additionally, this change alters the structural response from brittle to plastic.

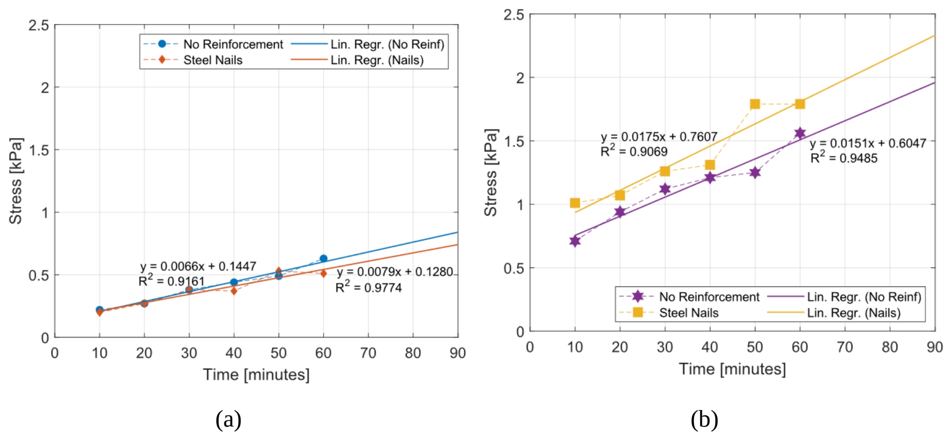

Fig. 6. Peak resistance within the initial 2 mm observed across different testing durations (a), Peak measured post the initial 2 mm for varying testing durations (b)

To summarize, while the presence of reinforcement initially leads to a slight reduction in static yield strength, for larger displacements it significantly enhances the shear load bearing capacity, resulting in an overall system improvement.

4 Conclusion

Based on the results obtained from this experimental campaign, it becomes evident how crucial it is to characterize shear strength in the realm of 3D concrete printing. Through the utilization of innovative experimental methods such as the shear box test and the incorporation of steel reinforcements, a precise evaluation of the increase in shear strength has been made possible, highlighting the advantages of reinforcement in enhancing the connection between concrete layers. This approach enables not only

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an initial estimation of shear strength but also a time-dependent analysis by simultaneously pouring concrete into both chambers of the shear box. Moreover, the use of reinforcements presents a twofold impact that deserves attention: they slightly mitigate the initial peak observed at lower sliding displacements, indicating the initiation of shear strength mobilization, while significantly influencing the brittle shear behaviours and introducing a degree of plasticity. These findings open avenues for further exploration of interlayer bonding, particularly by investigating the interaction between the time elapsed between successive layer depositions and the material's strength development. Future developments could involve advancing the setup to reduce formwork friction, albeit minimally, potentially by modifying the material selection to improve structural durability and longevity during extended-term testing, thereby enhancing the overall accuracy of evaluations.

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