

# Mechanical characterization of 3D printed concrete subjected to dynamic loading

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**Abstract.** In concrete structures realized by digital fabrication techniques, such as 3D concrete printing, under severe dynamic loadings (e.g. earthquakes and impact loads), the strength at the bond interfaces between layers is weak. Since these contact zones, also referred as cold joint, could potentially compromise the structural stability and also the durability of printed elements, their behaviour under high dynamic loads is fundamental to investigate. An experimental program on 3D printed concrete elements varying the waiting time, through medium and high strain-rate tensile tests is running, with a Hydro-Pneumatic Machine and a modified Hopkinson tensile bar respectively. The results of dynamic tensile tests at three different strain rates ( $10^{-5}$ , 50 and  $200 \text{ s}^{-1}$ ) on 3D printed cementitious elements for waiting times of 0min, 10min and 30 min have been presented, in terms of Dynamic increase factors DIF versus strain rate, showing a behaviour highly strain-rate sensitive, recording an increase in tensile strength DIF up to 7.6 in the case of high strain-rate and waiting time of 30 min. The results exhibited a decrease in the dynamic interface tensile strength with the waiting time up to over 90% for a medium strain-rate and over 20% for a high strain-rate.

## 1 Introduction

Additive manufacturing (AM) technologies, such as 3D-printing or layered extrusion technique, are arousing an increasing interest also in the construction sector, and in particular in the concrete application, for fabricating 3D structures directly from a digital model in successive layers usually layer upon layer [1].

The adoption of additive manufacturing technologies potentially brings a number of advantages [2], but at the same time suffers from a number of drawbacks, which limited their spread. Specifically, the layered extrusion technology necessarily creates interfaces between subsequent deposited layers, namely “Cold Joint”. These surfaces might create a potential zone of weakness into the printed structures [3] and depend mainly on the waiting time, i.e. the time between the printings of two successive layers [4]. In addition, the 3D printed

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elements present a less performing behaviour when subjected to dynamic loads as the waiting time increases, making crucial the assessment of the materials response under severe dynamic scenarios which could occur during their lifetime, such as earthquake and blast events.

So far, no dedicated approaches were reported on the bond of interface between 3D printed layers to examine its dynamic characteristics, at different strain-rate levels, with respect to static conditions.

The present work focuses on the determination of dynamic properties of printed concrete elements and, in particular, on the characterization of the interface behaviour between subsequent layers. In order to this, an experimental test was performed. This investigation is aimed at assessing the effect of the waiting time on the interlaminar strength of the interfaces and is based on failure tensile tests at different strain rates, in order to quantify the effect of dynamic loads on the behaviour of printed elements.

## 2 Materials and methods

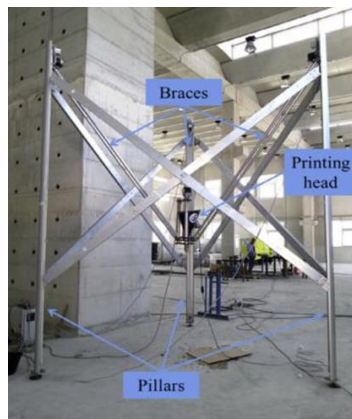
The experimental campaign on printed and unprinted elements has been conducted. The first elements have been realized using the extrusion-based 3D-printing application, while the second ones have been produced by means of traditional cast process. The response of samples has been compared, in order to define accurately the different behaviour of printed concrete elements with respect to bulk concrete elements, when subjected to dynamic loading conditions.

### 2.1 Mix proportions

The mix used for 3D printing can be defined as a mortar mix having an optimal rheological balance, an important requirement for satisfying the workability and buildability properties [5, 6]. The mix ratio presented by Asprone et al. [7] has been adopted and for sake of simplicity has not been reported herein.

### 2.2 Technological Process

The 3D printing system used was a simple apparatus characterized by a controlled extrusion in the x, y and z planes. The printing material is extruded by means of an endless screw towards the circular nozzle. The triangular printing area is characterized by sides of 4.0 m, and the printing head is controlled by 3 braces that move along the pillars (see Fig.1).



**Fig. 1.** BigDelta WASP 3D printing system

### 2.3 Sample preparation

Cylindrical samples consisted of two printed layers with thickness of 10 mm each and diameter of 20 mm and with a deposition rate of 2000 mm/m. The process begins by means of loading the 3D printing apparatus with the mortar mix, then depositing the layers consecutively, maintaining different waiting times  $T_s$ .

Specifically, three batches of three layered specimens were prepared. Each batch is characterized by the same material specifications above-described and by different intervals  $T_s$  between depositions of two subsequent layers ( $T_s=0$  min,  $T_s=10$ min,  $T_s=30$ min). These specimen groups were compared with bulk group, in both static and dynamic loading conditions. The Table 1 shows clearly the labels given to each sample. Samples are left to cure at a room temperature, for about 28 days.

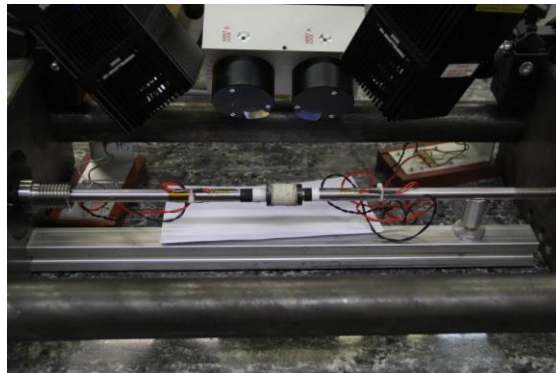
**Table 1.** Batches of layered and un-layered specimens.

	Static testing	Dynamic testing ( $\epsilon = 50 \text{ s}^{-1}$ )	Dynamic testing ( $\epsilon = 200 \text{ s}^{-1}$ )
Unprinted (bulk)	2L_001 2L_002 2L_003	2L_001m 2L_002m 2L_003m	2L_001h 2L_002h 2L_003h
Printed ( $T_0=0$ )	2L_T0_001 2L_T0_002 2L_T0_003	2L_T0_004m 2L_T0_005m 2L_T0_006m	2L_T0_004h 2L_T0_005h 2L_T0_006h
Printed ( $T_0=10$ min)	2L_T10_001 2L_T10_002 2L_T10_003	2L_T10_004m 2L_T10_005m 2L_T10_006m	2L_T10_004h 2L_T10_005h 2L_T10_006h
Printed ( $T_0=30$ min)	2L_T30_001 2L_T30_002 2L_T30_003	2L_T30_004m 2L_T30_005m 2L_T30_006m	2L_T30_004h 2L_T30_005h 2L_T30_006h

### 2.4 Testing setup

The experimental program was developed in the DynaMat Laboratory of the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) of Lugano.

Tensile failure tests under static conditions were performed, in order to compare the results from dynamic characterization ranging from medium and high strain-rates. As reference strain rate the ratio between test velocity and specimen gauge length is considered. Specifically, for medium strain-rate tests ( $\epsilon = 50 \text{ s}^{-1}$ ) a Hydro-Pneumatic Machine (HPM) with testing velocity of about 1m/s was used, as showed in Fig. 2.



**Fig. 2** Hydro-Pneumatic Machine for medium strain-rate tests

For investigating tensile behaviour under high strain-rate tests ( $\dot{\epsilon} = 200 \text{ s}^{-1}$ ) a Modified Hopkinson tensile Bar (MHB) apparatus with testing velocity of around 4 m/s was used (see Fig. 3). More details on the functioning of two systems can be found in different works [8, 9, 10, 11].



**Fig. 3** Hydro-Pneumatic Machine for medium strain-rate tests

### 3 Results and Discussion

Tensile test results can be used to investigate the behaviour of the unprinted and printed concrete subjected to a dynamic regime, at different strain rates and characterized by different waiting times. A simple value of imposed strain rate, equal to the ratio between strain velocity and initial specimen length, was considered during the testing procedure.

A first data processing in terms of average tensile strength exhibited by all samples for each strain-rate and for each waiting time, with the corresponding standard deviation, is showed numerically in the Table 2.

**Table 2.** Average Tensile strength  $\sigma$  (MPa).

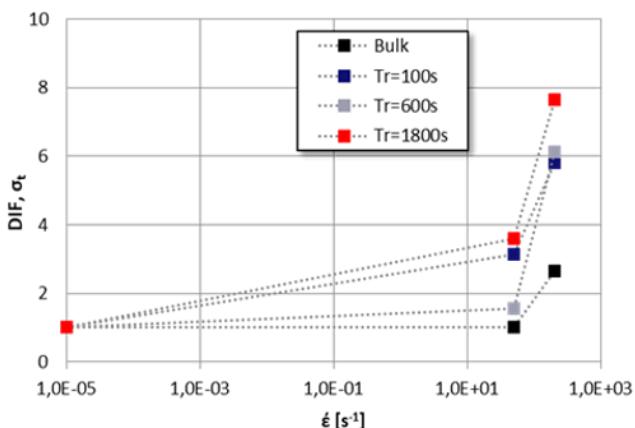
	Static testing	Dynamic testing ( $\dot{\epsilon} = 50 \text{ s}^{-1}$ )	Dynamic testing ( $\dot{\epsilon} = 200 \text{ s}^{-1}$ )
Unprinted (bulk)	3,15 ( $\pm 1,18$ )	3,16 ( $\pm 0,48$ )	8,31 ( $\pm 0,23$ )
Printed ( $T_0=0$ )	1,34 ( $\pm 0,3$ )	4,19 ( $\pm 1,3$ )	7,76 ( $\pm 1,39$ )
Printed ( $T_0=10\text{min}$ )	1,03 ( $\pm 0,3$ )	1,59 ( $\pm 1,05$ )	6,3 ( $\pm 1,27$ )
Printed ( $T_0=30\text{min}$ )	0,46 ( $\pm 0,23$ )	1,65 ( $\pm 0,05$ )	3,51 ( $\pm 0,54$ )

\*Terms in parentheses represent standard deviation values

The results reveal an increase in tension with the testing velocity and a decrease with time of waiting in the deposition of layers, confirming that the interface is a point of considerable weakness in the printed element.

Moreover, as expected the specimen failure shows a clear decreasing trend with the testing velocity. The dynamic behaviour appears strain-rate sensitive and shows a decrease in the dynamic interface tensile strength with the waiting time up to over 50% for a high strain-rate and over 40% for a medium strain-rate with respect to unprinted elements.

Average tensile strength values have been elaborated in terms of Dynamic Increase Factor (DIF) in relation with the strain-rate condition (see Fig. 4); the results highlight the growth of the gap between static and dynamic loading conditions with increases in strain-rate, up to a maximum DIF value of about 7.6 for high strain-rate of  $200 \text{ s}^{-1}$  and a waiting time of 30 minutes.



**Fig. 4** Tensile strength DIF–strain rate relationships, at different waiting times.

A comparison between the different loading conditions, in terms of tensile stress exhibited by every specimen, with varying the waiting time, shows an increase in strength greater than 100% from a lower to a higher applied strain-rate.

## 4 Conclusions

The present paper dealt with the characterization of layered extruded concrete elements under dynamic tensile loads, considering different waiting time as the main experimental variable. Strain-rate controlled tests were performed, using HPM and MHB devices, at strain-rates ranging from  $10^{-5}$  to  $200 \text{ s}^{-1}$ .

Specifically, strain-rate sensitivity was evidenced for high strain-rate levels whereas, within the intermediate strain-rate range, mechanical properties were not significantly enhanced.

In particular, the tensile strength DIF increased up to 7.6, for high strain-rate of about  $200 \text{ s}^{-1}$  and a waiting time of 30 minutes. The dynamic tensile results quantified the increase in tensile failure stress at the investigated strain-rate values, presenting a quasi-linear trend with the waiting time.

The development of mechanical characterization of interfaces in 3D concrete under dynamic loading results an important aspect in order to quantify the loss of resistance and the failure mechanism. A safety factor can be defined for contributing to design regulatory

requirements with particular reference to the suitability against dynamic actions such as earthquakes, blasts etc.

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