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Desarrollo de un método de refuerzo en proceso de impresión 3D de hormigón con aleación de Nitinol con memoria de forma
Development of an in-process reinforcement method in 3d concrete printing with nitinol shape memory alloy

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Resumen-- **El concepto de fabricación digital en la industria de la construcción se refiere al proceso de construcción de estructuras mediante robots con materiales cementosos. Para aumentar la resistencia a la tracción del hormigón como material principal en la impresión 3D de hormigón (3DCP), es necesario reforzar las estructuras con un segundo material. El refuerzo en 3DCP se realiza de tres maneras: refuerzo preinstalado, refuerzo en proceso y método de refuerzo postinstalado. En el método de refuerzo en proceso, en el que el refuerzo se realiza durante la impresión, es uno de los retos en los que muchos investigadores intentan trabajar y presentar un método práctico. Uno de los métodos de refuerzo en proceso que fue propuesto por los investigadores en esta área de conocimiento, es la "inserción de uñas en U", donde los materiales de refuerzo en forma de U se incrustan en las capas recién impresas durante la impresión de forma automática, y las capas serán conectadas por estas u-uñas. En este estudio, los autores realizaron una simulación en el software de elementos finitos Abaqus. Se propuso el Nitinol SMA como material de refuerzo y se modelaron las muestras con SMA U-nails y se simuló la prueba de flexión en tres puntos en el software para ver el efecto del uso de un nuevo material en el método de refuerzo mencionado. También se modeló una muestra sin material de refuerzo para tener una muestra de control y, por último, se compararon los resultados con diferentes materiales de refuerzo..**

Palabras clave— 3DCP; Refuerzo; SMA; Nitinol; Fabricación aditiva..

Abstract—**Concept of digital fabrication in construction industry, refers to the process of constructing structures by robots with cementitious materials. To increase in tensile strength of concrete as the main material in 3D concrete printing (3DCP), reinforcement the structures with a second material is necessary. Reinforcement in 3DCP is done in three ways: pre-installed reinforcement, in-process reinforcement, and post-installed Reinforcement method. In the in-process reinforcement method where reinforcement is done during printing, is one of the challenges which many researchers try to work on and present a practical method. One of the in-process reinforcement methods which was proposed by researchers in this area of knowledge, is "U-nails insertion", where U-shape reinforcement materials are embedded into fresh printed layers during printing automatically, and layers will be connected by these u-nails. In this study, a software simulation was done by authors in Abaqus finite-element software. Nitinol SMA was proposed as the reinforcement material and the samples with SMA U-nails were modelled and three-point bending test was simulated in the software to see the effect of using new material in the mentioned reinforcement method. A sample without reinforcement material was modelled, too, to have a control sample and finally results with different reinforcement materials were compared.**

Index Terms— 3DCP; Reinforcement; SMA; Nitinol; Additive manufacturing.

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I. INTRODUCTION

Digitalization in industries increases efficiency and it is due to the concept of the digitalization which reduces direct and indirect costs beside increasing in accuracy to produce products. In this case direct costs are the costs which money is spent directly to produce desired products and indirect costs are the costs where are not directly spent such as time factor, environmental and social impacts (Bharam Ahadi, 2023). Digitalization in construction industry is being happened in different phases. 3D concrete printing (3DCP) which is also known as additive manufacturing (AM), digital fabrication (DF) or solid-form technology (SFF) is the final phase of digitalization in construction industry.3DCP is the technology of concrete extrusion from a nozzle to form a structure which was designed in a 3D designing area software. In any 3d printing process the information from a cad file is stored in a stereolithographic (STL) and is subsequently transformed to layer-by-layer format. This layer-by-layer information is directly transformed to the printer's software (Khan, 2020;2018;2018). In comparison to traditional construction methods 3DCP presents a structure in a significant shorter time and with more accuracy. In this method, the needs to manpower are minimized and it makes 3DCP as safe method in term of human injuries. Needs to formwork in this type of construction are eliminated completely and COs emissions is lees when compared to conventional construction methods (Xiao, 2022; Feng en al., 2015; Tay et al., 2017; Geetha et al., 2022; Buswell et al., 2022). 3D concrete printing is being used in two methods in term of printing mechanism: i) powder-bed fusion and 2) Extrusion-based printing (Bahram, 2022; Khan, 2020). A powder-bed printer works on the principal of the depositing of a layer of powder on the build surface subsequently applying binder jet on the desired path as per the required geometry. The advantage of this method when compared to extrusion-based printing method is the freedom to print complicated architectures which cannot be smoothly realized by the extrusion-based printing method (Bahram, 2022; Khan, 2020;Ahadi, 2022;2022). In the extrusion-based 3d concrete printing method a cement-based concrete extrudes from a nozzle and the trowel makes a finished smooth surface through the build-up subsequent layers (Bharam Ahadi, 2023).

A. *Materials in 3D Concrete Printing*

The properties and printability of the concrete is greatly influenced by its ingredients and mix proportion (Geetha et al., 2022). She also set up an experimental study to optimize mortar mix for 3DCP. They used fly ash as a replacement to sand and observed that compressive strength of the samples enhanced by 20%. Concrete mix which will be used in 3DCP, should meet some criteria. These features are called printability of the concrete mix. Viscosity of concrete mix must be low to be flowable in the printer's pipes while its static yield stress should be sufficient to allow upper layers to be built over it after printing (Khan, 2020). Concrete mix usually consists of binder and fine sand aggregates along with mineral admixtures or additives. ((Khan, 2020; Ma et al., 2018). Ordinary Portland cement (C), fly ash (FA), granulated blast furnace slag, silica fume (SF) and Nano silica are used in different portion to form a binder (Khan, 2020).

B. *Reinforcement in 3D Concrete Printing*

Tensile strength is defined as the maximum stress that a material can bear before breaking when it is allowed to be stretched (Pal et al., 2022). Regarding the low tensile strength of concrete, reinforcement of the structures which are constructed by 3DCP method, is necessary to response to the loads which structures may face during utilization (Ahadi, 2022). There are three main reinforcement methods in 3DCP: a) pre-installed reinforcement b) post-installed reinforcement and c) In-process reinforcement (Ahadi, 2022). In the pre-installed reinforcement method, reinforcement materials such as steel rebars, meshes or cables are embedded before printing process. In the In-process reinforcement method, reinforcement materials are embedded automatically by the printer device or manually by human resources during printing process. Mesh reinforcement (Marchment et al., 2020), U-nails insertion (Wang et al., 2021), bars placement into the fresh printed concrete (Mechtcherine et al., 2021) and short fibre insertion are some of the creative In-process reinforcement method which were proposed by researchers. Geetah et.al. (2022) used Geogrid as the reinforcement material in their experimental study. They found that Geogrid reinforcement increases the stability between layers and helps to withstand more flexural strength. Al-Qutaifai et.al. (2018) used a fibre-reinforced Geopolymer mix which was designed for 3D concrete printing to improve interfacial bond strength between the adjoining layers. They observed that 1% of steel fibres reduces the workability by 4% and increases the flexural strength by 20%. Xiao et.al. (2022) used steel cables in the direction perpendicular to the printing interfaces and studied bending behaviour of the reinforced 3D printed concrete. Steel cables were embedded manually, and their proposed method was not an automatic reinforcement. They found that for specimens with suitable reinforcement, after cracking of the concrete in the tensile zone, cables began to resist the tensile strength and finally specimens failed when concrete reached to its compressive stress in the compression zone. Yang et.al. (2022) studied mechanical properties of 3D printing with Ultra-High-Performance Fibre-Reinforced Concrete (3DP-UHPFRC) with different factors such as fibre content, fibre type and printing direction. Their experiments indicated that specimens with 1vol% 6mm steel fibres was suitable for construction. They found that compressive strength of specimens is not depended on the steel fibre content significantly when loading is in the direction parallel to the layers printing direction. The same process was seen in the flexural tests too. Marchment and Sanjayan (Marchment et al., 2020) proposed a new automatic in-process reinforcement method. They modified the printer device and steel meshes were automatically placed in the printed layers and interlayer reinforcement was done automatically at the same time with concrete printing. Specimens were subjected to the three-point bending tests and cracking and ultimate moments for unreinforced and reinforced specimens were calculated. They found that steel mesh reinforcement increased the flexural moment by 170-290 % when compared to than that of unreinforced specimens. Hojati et.al (2022) proposed a new method for in-process 3DCP reinforcement. They used barbed-wires fencing wires with sharp thorn-like projections as a reinforcement component to improve tensile capacity and bond between printed layers. They observed that moment capacity and bond strength increased by 363% and 71% respectively.

The main aim of doing this study is to propose a new smart material for reinforcement of 3D concrete printings and investigate effect of using this material when compared to steel reinforcement. To see the effect of new reinforcement material, a numerical study was done, and samples were simulated in Abaqus finite-element (FE) software. Steel-reinforced samples, Nickel-Titanium (Ni-Ti) shape memory alloy (SMA) reinforced sample and an unreinforced sample were modelled in the software and sample were subjected to three-point bending test. Finally, maximum flexural moments were recorded for analysed sample and results were compared.

II. METODOLOGÍA

This study was conducted to investigate effect of using a new smart material in 3DCP structures. Regarding reinforcement challenges in 3DCP, creative reinforcement methods and smart materials, can help to improve structural behaviour of these type of structures. In this research, 3D concrete printing technology was explained, and various reinforcement strategies were discussed. Among existing reinforcement methods, in-process reinforcement method where reinforcement is done during printing, is the most important one regarding the concept of automation in construction and this type of reinforcement is the most difficult one due to its automatic process. The reinforcement material which was studies in this research is Nickel-Titanium (Ni-Ti or Nitinol) shape memory alloy (SMA) which has a smart behaviour in recovering its first shape.

A. Shape Memory Alloys (SMAs)

Shape memory alloys (SMAs) are the smart materials which can recover their initial shape after deformation. SMAs are characterized by shape memory effect (SME) and super elasticity (SE). In the SME behaviour of SMAs, if the material deforms by an external mechanical load, it can recover to its first shape by heating and in the SE behaviour of the SMAs, the material can be stretched or bend but mostly return to their original shape upon unloading.(Ahadi, 2022)SMAs have two stable phases with different crystal structures. State of SMAs is strongly depended on what temperature that they are in. The high-temperature is called austenite or parent phase and has a body centred cubic crystal structure, whereas the low-temperature phase is called martensite and is indicated by a lower symmetry and tetragonal, orthorhombic, or monoclinic crystal structure. Fig. 1 shows the geometric appearance of the austenite and martensite phases (Antonucci et al., 2015).

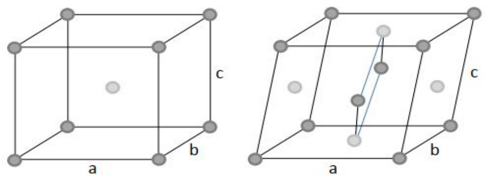

Fig. 1 Geometric appearance of austenite (left) and martensite (right) (Antonucci et al., 2015).

There is different composition of shape memory alloys such as gold-based alloys, Nitinol, cooper-based alloys etc. where Nitinol is the best alloy in acting as shape memory characteristics beside the other three remarkable properties like an excellent corrosion, have stable configuration and an almost perfect bio compatibility (Faiella et al., 2015).

B. U-Nail Reinforcement of 3D Concrete Printing

In 2020, Wang et.al. (2021) investigated the interlayer reinforcement of 3DCP by the in-process deposition of U-nails. A robotic 3D concrete printer was developed with a horizontal working space of 1.73 m. to see the effect of U-nail reinforcement different specimens with different U-nails thicknesses and intervals were tested. In the interface shear tests, they observed that the tensile strength was increased by increase in U-nail thicknesses and was decreased by in U-nails spacing. The U-nail which were used in the experimental study of Wang et.al was steel.

C. Finite-elements (FE) analysis

In this study, effect of using Nitinol SMA in U-nails reinforcement of 3DCP was investigated. At the first, a verification sample was modelled in Abaqus FE software to make sure that our software simulation works correctly. To verify the software simulation a sample exactly as the same as the experimental study of Wang et.al. (2021) with the dimensions of 10mmx10mmx20mm was modelled in software and the sample was analysed with the double-shear test and interlayer shear strength obtained 7.9 Mpa where in the real experiment the same parameter was 7.7 Mpa and the error is less than 5% and is acceptable for this simulation.

After verification of software simulation, specimens with the properties of the Table 1 were modelled.

TABLE I
SAMPLE PROPERTIES

Samples Name	a (mm)	b (mm)	C (mm)	Reinforcement Material
UPS	10	10	30	Unreinforced
S-PS	10	10	30	Steel
N-PS	10	10	30	Nitinol

Where a, b and c are as shown in Fig. 2.

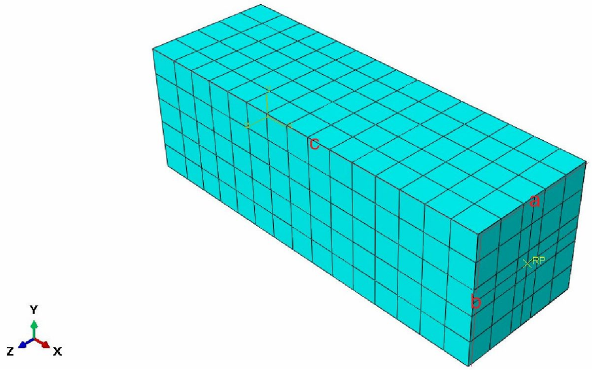

Fig. 2 . Schematically view of samples dimensions.

It should be noted that total length of the samples is 60 mm but to reduce time of analysis, just half of the beams were modelled, and moments and shear strength were recorded. Type of the load is displacement-control and Abaqus CAE 2018 was used to analyse models. properties of the Nitinol reinforcement which were used, is presented in the table 2 regarding the numerical study of Bykiv et.al (Bykiv et al., 2022).

TABLE II
PROPERTIES OF THE NITINOL MATERIAL

SMA	Niti
Density (gr/cm^3)	6.45
Young's module, (Gpa)	68.2
Poisson's Ratio	0.36
σ_s^{Am} (Mpa)	407.5
σ_f^{Am} (MPa)	428.3
σ^{Am} (Mpa)	127.2
σ_f^{Am} (MPa)	73.6
ε (m/m)	0.06
Alpha	0

III. RESULTS AND DISCUSSION

Fig. 3 shows bending moment versus vertical displacement for analysed samples. As it can be seen from the chart, UPS sample failed at the displacement of 13.8 mm and the moment strength at this displacement was recorded as 4.5×105Mpa, where the N-PS sample at the same displacement with UPS, recorded the moment resistance of 13×105Mpa, which shows an increase of approximately 189% in moment strength. S-PS sample recorded a moment strength of 14×105Mpa at the displacement of 13.8 mm which is 7% higher than that of SMA reinforcement. At beginning intervals (0 – 5mm) of the applied displacement, moment resistance of S-PS sample is 30% higher than that of N-PS sample and in continue (10mm–15mm)this difference decreases to 10% and this is because of the U-nails contributions where SMA U-nails regarding their super elasticity characteristic withstands more against applied stress as it can be seen in the Fig. 4.

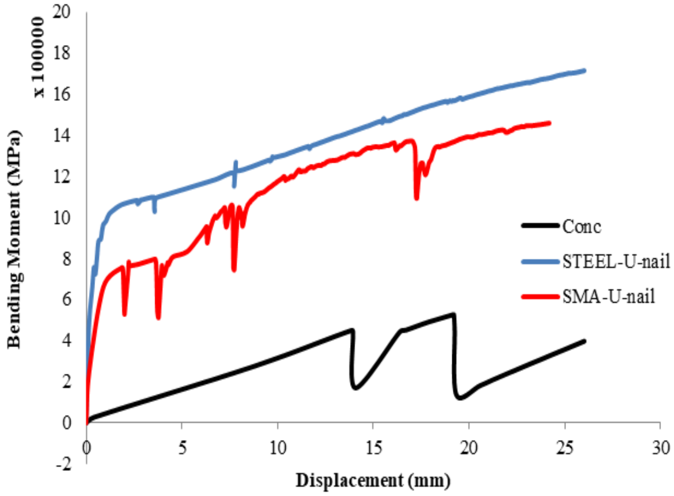

Fig. 3. Moment strength-displacement curve for samples.

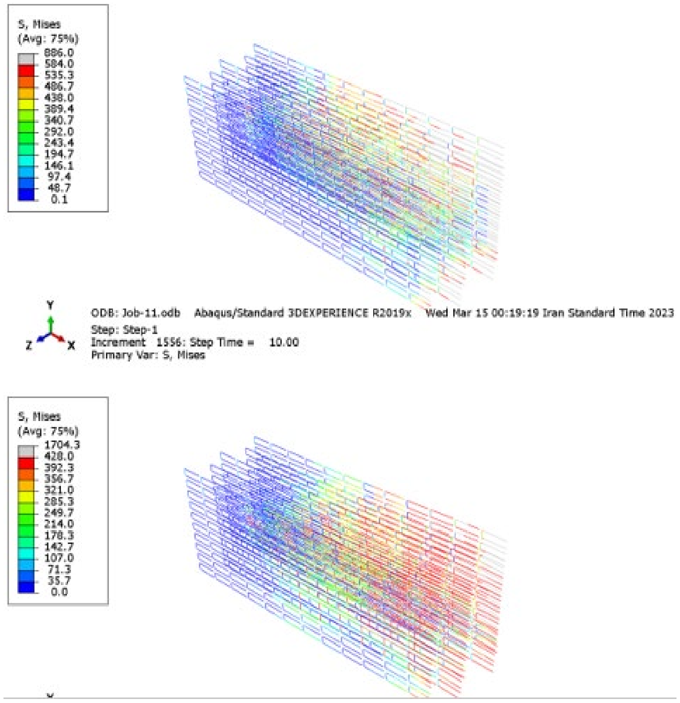

Fig. 4. Stress of U-nails after samples analysis a) steel U-nails and b) Nitinol U-nails.

Crack propagation in concrete in the N-PS sample is significantly more than that of S-PS sample and this is a confirmation the super elasticity behaviour of SMAs where they can stretch up to 8% where steel can have up to 2% strain. These failures can be seen in the Fig. s 5 and 6.

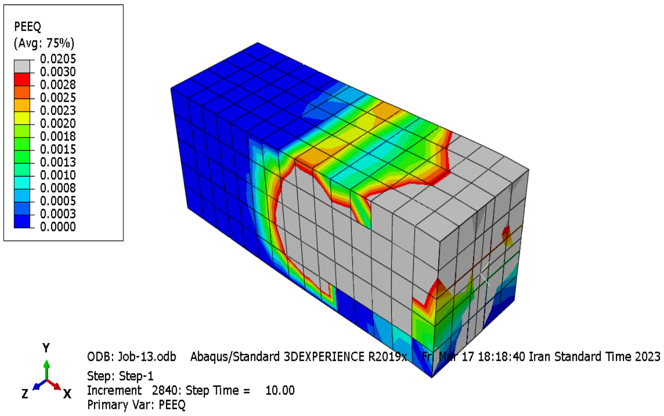

Fig. 5. Damage of the N-PS sample.

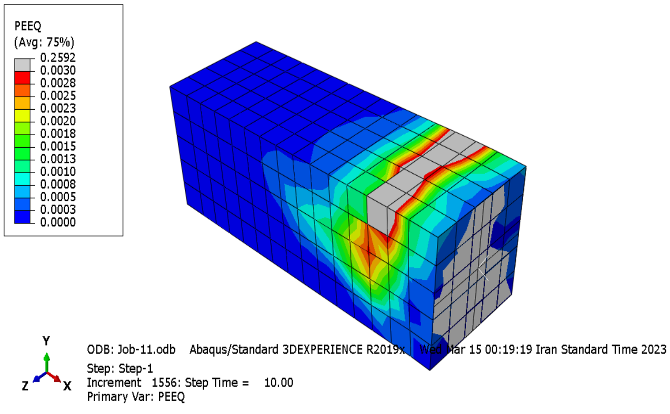

Fig. 5. Damage of the S-PS sample.

IV. CONCLUSIONS

In this research, possibility of using shape memory alloys in 3D concrete printing structures was investigated. Nitinol shape memory alloys was used as the reinforcement material in U-nail reinforcement method of 3DCP. Three samples were modelled in Abaqus finite-element software and samples were subjected to three-point bending test and finally moment strengths were recorded for samples and results were compared. The following conclusions can be drawn from this study:

- Regarding the lower modulus of elasticity of Nitinol when compared to steel, moment resistance of the samples reinforced with steel was higher than that of SMA reinforcement.
- Regarding the super elasticity behaviour of Nitinol SMA, the SMA reinforced sample showed be better behaviour in rate of increasement in moment resistance where the difference changes from 30% at the beginning to 10% at the end of the loading.
- In this research active behaviour of SMAs where they can reach to their first shape after deformation by heating, is not considered. By considering this feature of SMAs, it is expected that SMA reinforced sample to show higher moment resistance when compared to steel one.
- Due to the SE behaviour of SMAs, lower number of u-nails in N-PS sample were failed when compared to the u-nail of the S-PS.
- SMAs have enough potential to be considered as a reinforcement material in 3DCP structures regarding their SE and SME behaviour.

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