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# Digital Fabrication of Segmental Concrete Columns Prestressed with Iron-based Shape Memory Alloy Bars for Accelerated Bridge Construction

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**Abstract**

The combination of digital fabrication technology and prestressed segmental column construction holds great promise for the accelerated construction of bridges with material-efficient design. This study aims to explore this potential by introducing an innovative prestressed segmental column system that utilizes 3D printed concrete (3DPC) formwork and iron-based shape memory alloy (Fe-SMA) reinforcement for prestressing. To evaluate the proposed system's performance, large-scale experiments were conducted on two columns subjected to gravity and lateral loads. The experimental findings demonstrated that the columns were capable of withstanding lateral drifts of up to 5% without collapsing, and the 3DPC formwork exhibited no signs of premature failure or delamination. Additionally, the columns displayed self-centering characteristics, maintaining a residual drift of less than 1% up to a target drift of 3%. These results showcase the potential of the proposed prefabrication concept, which can enable the design of bridge columns that are both material-efficient and resilient to seismic actions

*Keywords:* Digital fabrication, 3D concrete printing, segmental column construction, Fe-SMA prestressing

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## 1. Introduction

The use of precast concrete in bridge construction has seen a notable increase recently due to its benefits, such as

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accelerated construction, enhanced quality control, reduced labor needs, and minimal traffic disruptions. Digital fabrication technology has the potential to further expedite the prefabrication process by employing customized stay-in-place formworks made with 3D printed concrete (Khoshnevis 2004, Gosselin et al. 2016). The use of 3DPC formwork can allow the fabrication of light-weight intricate/complex geometries in less time and eliminate the necessity for temporary formwork typically used in traditional construction, which can account for up to 30-60% of the total construction costs (Johnston 2008) and is a major source of construction waste (Dong et al. 2015).

While segmental construction with precast concrete has been around since the mid-20th century, primarily for bridge superstructures, its application to bridge piers and columns gained momentum in the mid-1990s, notably in the United States (Billington et al. 1999, Figg and Pate 2004). Notable applications include the Louetta Road Overpass in Houston and the Victoria Bridge in New Jersey, USA (Fawaz et al. 2019). These columns typically consist of prefabricated segments assembled on-site, along with footing and cap beams, with prestressing provided by unbonded tendons.

A key feature of prestressed segmental columns is their ability to exhibit controlled rocking under lateral loading, enabling self-centering characteristics. However, these columns have limited energy dissipation capabilities due to the high yield strength of conventional steel tendons (Yamashita and Sanders 2009). Various systems have been proposed to enhance the energy dissipation capacity of prestressed segmental columns (Motaref et al. 2014 and Wang et al. 2018). Another practical issue with prestressed segmental construction of columns is that conventional prestressing procedures involve the use of heavy mechanical equipment onsite, which is laborious and time consuming.

To address the issue of low energy dissipation and the requirement of mechanical prestressing & anchoring equipment with conventional prestressing steel tendons/strands, an alternative solution is to use smart materials such as iron-based shape memory alloy (Fe-SMA) bars for prestressing. Fe-SMA belongs to a class of smart materials, which have a unique ability to recover inelastic strains on heating. This property, known as the shape memory effect, can be used to generate recovery stress in the Fe-SMA if the recovery of strains on heating is prevented by clamping/end anchorage (Raza et al. 2022a). This property of Fe-SMA has led to a number of different applications for structural retrofitting purposes, as outlined in Shahverdi et al. 2022. In addition, Fe-SMA has strong energy dissipation characteristics owing to its high ductility, which can possibly address the issue of low energy dissipation in conventionally post-tensioned segmental columns.

This study aims to integrate digital fabrication technology with segmental construction methods and a simplified prestressing technique using Fe-SMA reinforcement for accelerated bridge construction. The main advantages of segmental construction with 3DPC formwork over traditional formworks are that 3DPC formwork becomes a permanent part of the structure, eliminating the need for demoulding, and it allows for the fabrication of customized geometries with material-efficient designs. For this purpose, two segmental columns reinforced with Fe-SMA bars were fabricated using stay-in-place 3DPC formwork. To investigate the feasibility of the proposed segmental column system, large-scale experiments were conducted under combined gravity and lateral loading. This paper presents a summary of the main findings of the experimental program. More details regarding the study can be found in Raza et al. 2024.

## 2. Experiments

### 2.1. Proposed Prefabrication Concept

In the proposed column system, unreinforced 3DPC cylindrical shells act as permanent formwork for the reinforced concrete core to facilitate the fabrication process of the column segments. The core of the column is reinforced with continuous Fe-SMA and steel bars spanning across the segments, to simplify the prestressing process and provide energy dissipation. Fig. 1 shows the step-by-step process involved in the fabrication and assembly of the segmental column system. The unreinforced hollow 3DPC formwork rings are fabricated first for the segments using an extrusion-based robotic printer, as shown in Fig. 1 (a). A reinforcement cage made of discontinuous steel bars, ties, and corrugated steel ducts is installed within the formwork rings, as shown in Fig. 1 (b). The ducts are provided for facilitating the passage of the continuous Fe-SMA and steel bars through the prefabricated segments during the column assembly. In the next step, cast concrete is poured into the segments, as illustrated in Figure 1 (c). The segments are then stacked over the precast footing shown in Fig. 1 (d). Cement mortar is applied at segment interfaces to facilitate the bonding between the segments, as shown in Fig. 1 (e). The ducts of the steel and Fe-SMA bars are grouted next, as shown in Fig. 1 (f). The assembled column segments are displayed in Fig. 1 (g). Finally, the top loading block/cap beam is cast, as shown in Fig. 1 (h).

(a) 3D printing of formwork (b) Installation of reinforcement and ducts (c) Cast concrete filling (d) Cast footing with reinforcement

(e) Stacking of segments (f) Grouting of reinforcement (g) Assembled column segments (h) Completed column assembly

Fig. 1. Prefabrication procedure for segmental columns with 3D printed formwork (Adapted from Raza et al. 2024)

### 2.2. Design Details

Two columns specimens were considered for assessing the feasibility of the proposed prefabrication concept. The column specimens consisted of four cylindrical segments, with 380 mm diameter and 350 mm height, as shown in Fig. 1. In both specimens, the cylindrical formwork consisted of a single 3DPC filament that had a thickness of 20 mm and a layer height of 10 mm. The inner core of the specimens consisted of cast concrete reinforced with steel and Fe-SMA bars. Specimen S1 was reinforced with 4ø18 Fe-SMA bars, 2ø14 steel bars, and 6ø14 discontinuous steel bars in each segment, as shown in Fig. 1 (a) and (c). Note that discontinuous reinforcement refers to bars that terminate in each segment. Specimen S2 had the same amount of Fe-SMA reinforcement as S1, but double the amount of steel reinforcement i.e. 4ø14 steel bars, as shown in Fig. 2 (c). The total longitudinal reinforcement ratio in specimens S1 and S2 was 1.17% and 1.44%, respectively, whereas the ratio of steel to Fe-SMA bars in the specimens was 0.3 and 0.6, respectively. It is important to note that Fe-SMA bars had a plain configuration in the middle of the column and were threaded at the anchorage region. The plain configuration was kept in the middle region to reduce the strain concentration in Fe-SMA bars and corresponding loss in prestress (Raza et al. 2022a, Raza et al. 2023). The compressive strength of 3DPC formwork and cast concrete for both specimens on the test day was 84 MPa and 87 MPa, respectively.

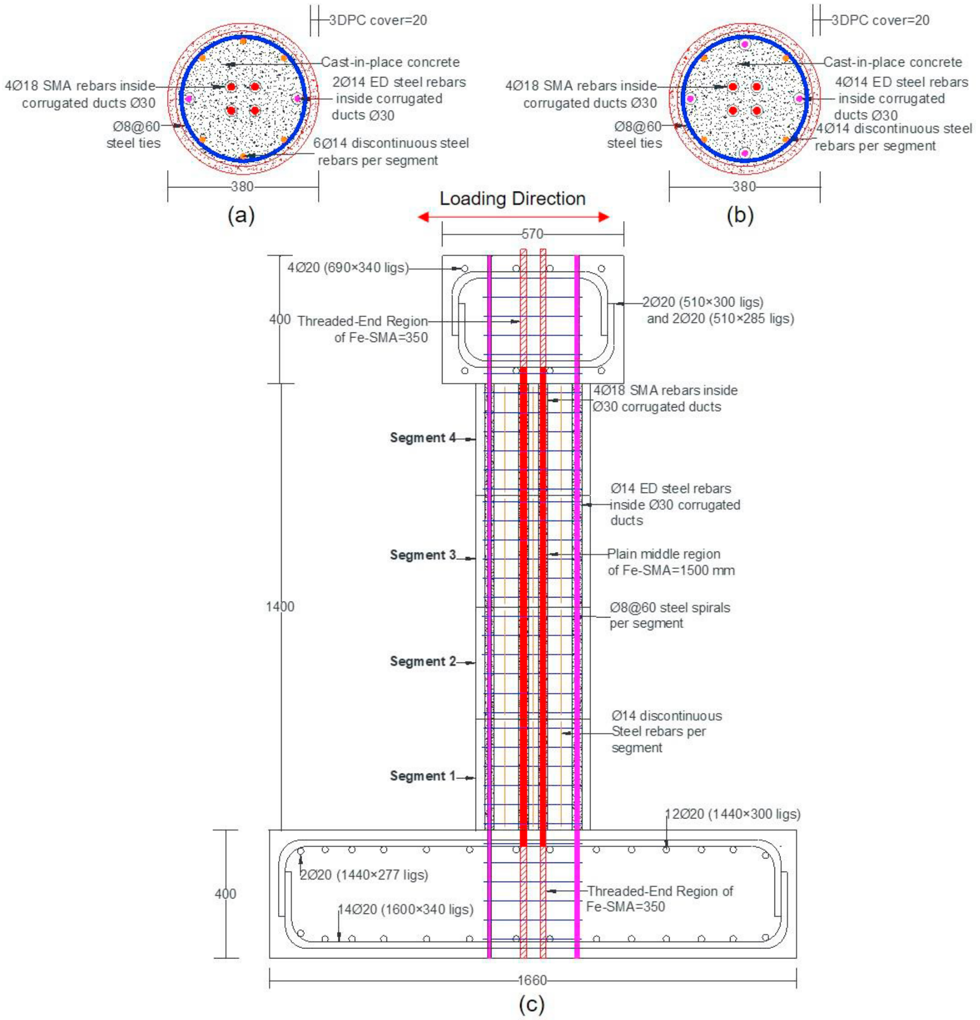


Fig. 2. Design details of columns: a) S1-cross-section; b) S2-cross-section; c) front elevation (reprinted from Raza et al. 2024)

### *2.3. Prestressing of Columns via Activation of Fe-SMA bars*

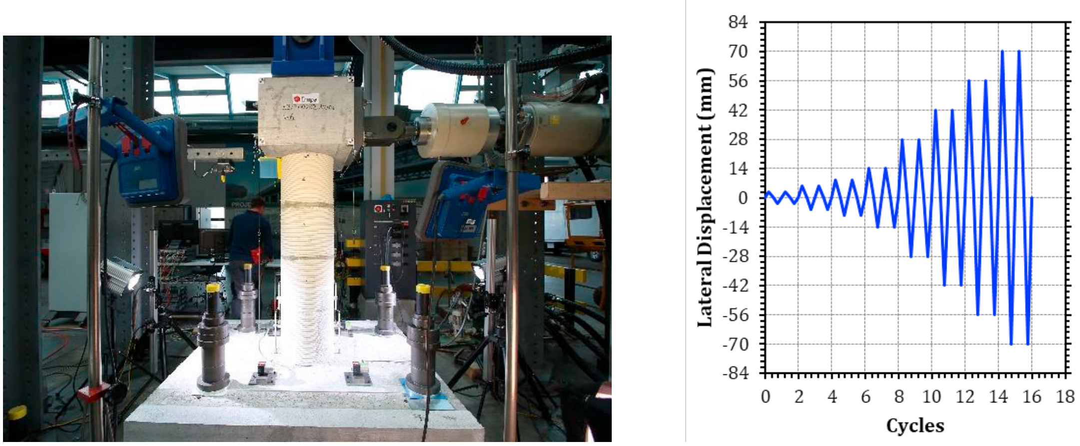
The Fe-SMA bars in the columns were activated using electric resistive heating. Each pair of Fe-SMA bars was joined into a single uninterrupted conductor prior to concrete casting. This was accomplished by welding a short horizontal segment of the same bar type halfway along their embedded length in the footing, as depicted in Fig. 3 (a). This configuration ensured that each pair of bars could be activated simultaneously, with connection points accessible only from above. Additionally, at the upper end of the column, Fe-SMA bars extended by 100 mm to accommodate the clamping of power supply connectors, as illustrated in Fig. 3 (b). The bars were heated to a target activation temperature of 180 °C. The temperature development was monitored with thermocouples mounted on the bars and the power supply was turned off after reaching the target activation temperature. The effective recovery stress of Fe-SMA bars on heating to 180 °C is approximately 300 MPa.

(a) (b) (c)

Fig. 3. Activation setup for Fe-SMA bars: a) welding of bar pair for electrical continuity; b) clamps connected to bar pair protruding from the column top for power supply; c) complete activation setup

### 2.4. Experimental Setup and Loading Protocol

The columns were tested under combined axial load and incrementally increasing displacement-controlled cyclic lateral loading using the setup shown in Fig. 4 (a). The axial load on the column consisted of the gravity load and prestressing load due to activation of Fe-SMA bars. The gravity load applied to both columns was 468 kN and corresponded to an axial load ratio of 0.057. The prestressing load due to the activation of Fe-SMA bars was about 280 kN, corresponding to an axial load ratio of 0.036. More details about the determination of prestressing load can be found in Raza et al. 2024. The lateral loading protocol applied to the column is shown in Fig. 4 (b). The experiment was stopped at 5% drift due to the limitations of the experimental setup.



(a) (b)

Fig. 4. (a) Experimental setup; (b) lateral loading protocol

## 3. Results and Discussion

### 3.1. Force-Displacement Behavior and Damage Progression

The hysteretic force-displacement behavior of specimens S1 and S2 is shown in Fig. 5 (a). Both specimens were able to withstand 5% lateral drift without collapse. The maximum lateral strength of S2 was about 15% higher than S1 due to the higher amount of longitudinal reinforcement. However, the increase in strength was not proportional to the increase in longitudinal reinforcement, i.e. a 15% increase in strength was observed for a 30% increase in longitudinal reinforcement ratio. This was mainly because the additional reinforcement in S2 was installed at the neutral axis instead of the extreme loading faces. An accelerated degradation in strength was observed for S2 compared to S1 because it resisted higher loads, resulting in greater damage to the concrete.

The damage to the column specimens at the end of the experiment is shown in Figs. 5 (b) and (c). A part of the 3DPC formwork was detached from the core concrete at 5% drift in S1, whereas detachment/delamination of 3DPC formwork was not observed for S2. Due to the segmental nature of the columns, flexural cracks were developed mainly at the segment joints (leading to joint opening) instead of within the formwork, whereas vertical splitting cracks owing to hoop strains were observed in the 3DPC formwork at the bottom segment. Overall, the 3DPC formwork didn't show a premature failure/delamination in both columns.

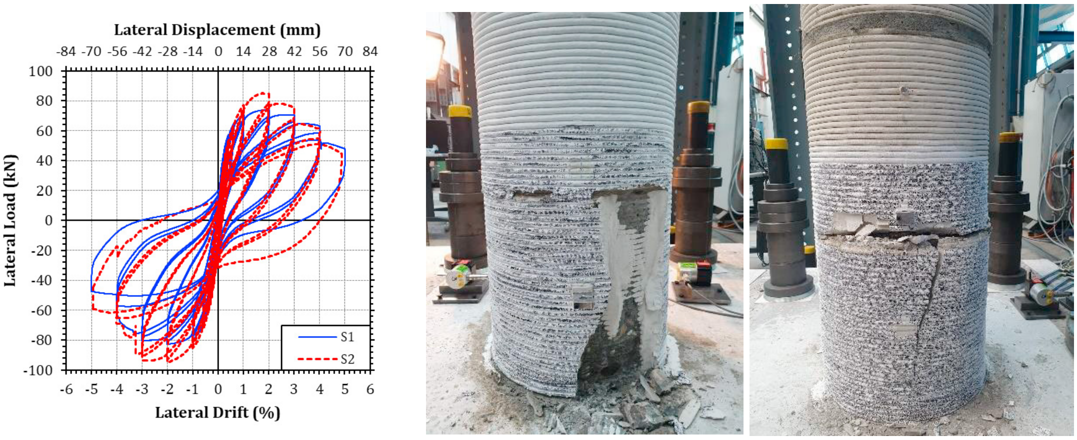


Fig. 5. (a) Hysteretic force-displacement behavior of the columns; b) Damage to S1 at the end of experiment; c) Damage to S2 at the end of experiment

### 3.2. Self-Centering and Residual Drifts

The average residual drifts of the tested columns at target drifts of 3%, 4% and 5% are shown in Fig. 6 as a function of the steel to Fe-SMA reinforcement ratio. The results show that on increasing the steel/Fe-SMA reinforcement ratio, the residual drifts showed an increasing trend. However, the increase in residual drifts was not proportional to the increase in reinforcement ratio because this is dependent on the location of the steel bars. In the current study, the additional steel bars in S2 were placed at the neutral axis and therefore experienced smaller strains/residual strains, which in turn resulted in a smaller increase in residual drifts. The results also indicate a drastic increase in the residual drift at 5% drift compared to the target drifts of 3% and 4% owing to greater damage to the 3DPC formwork and higher residual strains in reinforcement. In addition, Fe-SMA bars are expected to exhibit plastic behavior at high drifts, resulting in the loss of initial recovery stress and in turn increase in the residual drifts of the column.

The results show that the self-centering and energy dissipation behavior of precast segmental columns mainly depends on the steel to Fe-SMA reinforcement ratio rather than the actual diameter of the bars. For upscaling the proposed fabrication technique to large columns, this ratio needs to be selected based on the desired level of performance in terms of self-centering and energy dissipation. Its' important to note that Fe-SMA bars are typically available in lengths of 5m. They can be lapped by welding to be used in lengths of 10-30 m for real-scale bridge piers

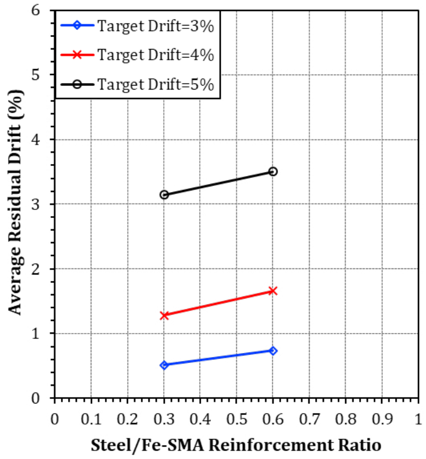


Fig. 6. Effect of Steel/Fe-SMA reinforcement ratio on the residual drifts of segmental columns with 3D printed concrete formwork

## 4. Conclusion and Future Outlook

This study introduced an innovative prefabrication concept for accelerated construction of segmental bridge columns. The proposed approach combines digital fabrication technology with an advanced Fe-SMA-based prestressing technique. In the proposed prefabrication approach, hollow 3DPC shells are used as permanent formwork for the columns, thereby eliminating the need for temporary formwork used in traditional construction. The viability of the concept was assessed through large-scale experiments on columns subjected to combined gravity and quasi-static cyclic lateral loads. The results showed that the columns were able to withstand 5% drift without collapse and premature failure of 3DPC formwork. Furthermore, the columns showed self-centering up to a target drift of 3% due to the prestressing effect of Fe-SMA bars. It is expected that self-centering behavior could be further improved by increasing the initial prestressing level and varying the location of Fe-SMA bars within the cross-section.

Given the positive results of the feasibility study, future work could investigate optimized geometries for the formwork shells of segmental columns that can be fabricated efficiently through 3D printing, thereby making the next generation of columns lightweight. This could include overall shape optimization of the 3DPC formwork shells, geometric variation between the segments, and the integration of additional functionality including printing of formwork shells with integrated ducts.

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