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Performance of RC beams strengthened with self-prestressed Fe-SMA bars exposed to freeze-thaw cycles and sustained load

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A B S T R A C T

Iron-Based Shape Memory Alloys (Fe-SMA) have been recently used by researchers as a strengthening material for Reinforced Concrete (RC) beams. This material is relatively inexpensive compared to the traditional Nickel Titanium SMA (NiTi-SMA), which makes it feasible for large-scale structural engineering applications. The Fe-SMA is mainly characterized by the Shape Memory Effect (SME) phenomenon, which allows the material to recover the induced deformations through heating. When the pre-strained Fe-SMA bar/strip is anchored on the tension side of an RC beam using the Near-Surface Mounted (NSM) strengthening technique and is then heated to the activation temperature, a tension force (prestressing force) develops in the material, which results in enhancing the flexural capacity of the RC beam at service and ultimate load conditions. This paper investigates the long-term performance of RC beams strengthened with NSM Fe-SMA bars and exposed to severe freeze–thaw cycles and sustained loading. The results revealed that the strengthened beam was superior in flexural performance compared to the un-strengthened beam, and there was minimal degradation compared to other beams tested at room temperature.

1. Introduction

Fiber Reinforced Polymers (FRP) have been used extensively by researchers as viable materials to strengthen RC beams using both the externally bonded (EB) or Near-Surface Mounted (NSM) techniques. The NSM FRP strengthening technique has been proven to be the most efficient system of mounting the FRP strips/rods to the RC beam [1]. The NSM technique involves placing the FRP material in a pre-cut groove on the tension side of the RC beam and anchored at both ends to the beam. As the NSM FRP strengthening technique is intended for existing structures, the FRP material is not expected to be activated unless a further deformation/load is imposed on the beam. This process is called passive strengthening system, and the contribution of the strengthening material occurs mainly under ultimate load conditions [1]. The active strengthening technique is essential to improve the serviceability performance of RC beams under service load conditions. Active strengthening involves applying a prestressing force to the strengthening material, which causes a counter effect of the applied loads, and consequently, helps to close existing cracks, delay the formation of new cracks, and reduce deflection. However, as more strain is employed for the prestressing force, RC beams become more brittle [1,2]. The application of prestressed NSM FRP technique has evolved over the past two decades from indirect prestressing systems to a more practical direct prestressing system. In the indirect system, the FRP material is prestressed against external reaction frame [3,4], while the direct prestressing system involves the prestressing of the FRP material against the beam itself without the need for external reaction frame [5–7]. Despite the developments in the prestressed NSM FRP techniques, applying the prestressing force to FRP bars/strips is still a sophisticated and might be a too laborious process that involves the need of special anchorage and jacking tools.

Recently, some researchers proved the efficiency of Iron-Based Shape Memory Alloys (Fe-SMA) as an active strengthening material using the NSM technique [8,9]. In the case of Fe-SMA, a prestressing force can be generated by heating the material above the activation temperature without the need for jacking tools. Additionally, the yielding nature of the Fe-SMA allows for a ductile behavior/failure of RC beams unlike the FRP-strengthened beams [10–12].

Fe-SMA is a metallic alloy that mainly consists of iron, manganese, and chromium. The Fe-SMA is characterized by the Shape Memory Effect (SME), which reflects the capability of the material to recover its shape upon heating [13,14]. The Fe-SMA is more feasible than the Nickel Titanium SMA (NiTi-SMA) for large-scale structural engineering applications, as the former is made of relatively inexpensive constituent materials. More information about the material properties can be found in [15–20].

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Table 1
Test matrix.

Group	Name	Strengthening	Type of exposure	# of cycles	Sustained load
R	R-C R-SMA	N/A Fe-SMA bar	Room Temperature	N/A	N.A.
E	E-C E-SMA	N/A Fe-SMA bar	Freeze-Thaw, and sustained loading	650 cycles (7 months*)	50% of ultimate capacity of Beam E-C

* The beams were 6 months old when the freeze-thaw exposure started.

Table 2
Material properties of steel and concrete.

Beam	Concrete strength (MPa)			Steel yield strength f_y (MPa)	
	28 days	At testing	Age (month)	15 M bars	10 M bars
R-C R-SMA	39 ± 0.8	43 ± 0.6	2	451.4 ± 0.2	440 ± 2.2
E-C	35.3 ± 0.2	36.8 ± 0.9	16	505 ± 1.0	446 ± 4.0
E-SMA	36.9 ± 0.3	38.4 ± 1.0	16		

The manufacturer of the Fe-SMA materials used in this research reports that after the activation of the Fe-SMA, the material become as an integral part of the structural system and no shape transformation is expected as a result of ambient temperature variation [15]. This material property which makes it stable for external structural applications is attributed to the wide thermal hysteresis of the Fe-SMA material [16]. However, there is no information about the behavior of the Fe-SMA under thermal variation. Therefore, it is important to investigate the long-term performance of RC beams strengthened with Fe-SMA bars under environmental exposure and sustained loading.

This paper presents the findings of an experimental investigation of the performance of RC beams strengthened with Fe-SMA bars and exposed to freeze-thaw cycles and sustained loading. The beams were exposed to 650 freeze-thaw cycles under a sustained load of 50% of the ultimate capacity of the control un-strengthened beam. The performance of the beams exposed to the freeze-thaw cycles is compared with other beams tested at room temperature.

2. Experimental program

2.1. Testing matrix

Four RC beams in total were tested; the beams were divided into two groups based on the type of exposure: Group R (**R** refers to room temperature), and Group E (**E** refers to environmental exposure). Each group consisted of two beams; one beam was strengthened in flexure with an Fe-SMA bar (R-SMA beam and E-SMA beam), and one was a control un-strengthened beam (R-C beam and E-C beam) as presented in Table 1. Only beams E-C and E-SMA were subjected to sustained load during the exposure duration.

2.2. Description of the specimens

All the beams had the same cross-sectional dimensions and reinforcement details. Fig. 1 shows the geometric details of a typical beam, the instrumentation details, and the loading setup. All the beams were designed as under-reinforced beams according to the CSA A23.1-04 [21]. The shear reinforcements consisted of 10 M two-legged closed stirrups provided at a spacing of 150 mm to prevent shear failure. The beams were reinforced with two 15 M bars in tension and two 10 M bars in compression with a total steel cross-sectional area of 400 mm^2 and 200 mm^2, respectively. Table 2 shows the steel and concrete material properties.

2.3. Preparation of Fe-SMA bars

Two Fe-SMA bars were used to strengthen the R-SMA and E-SMA

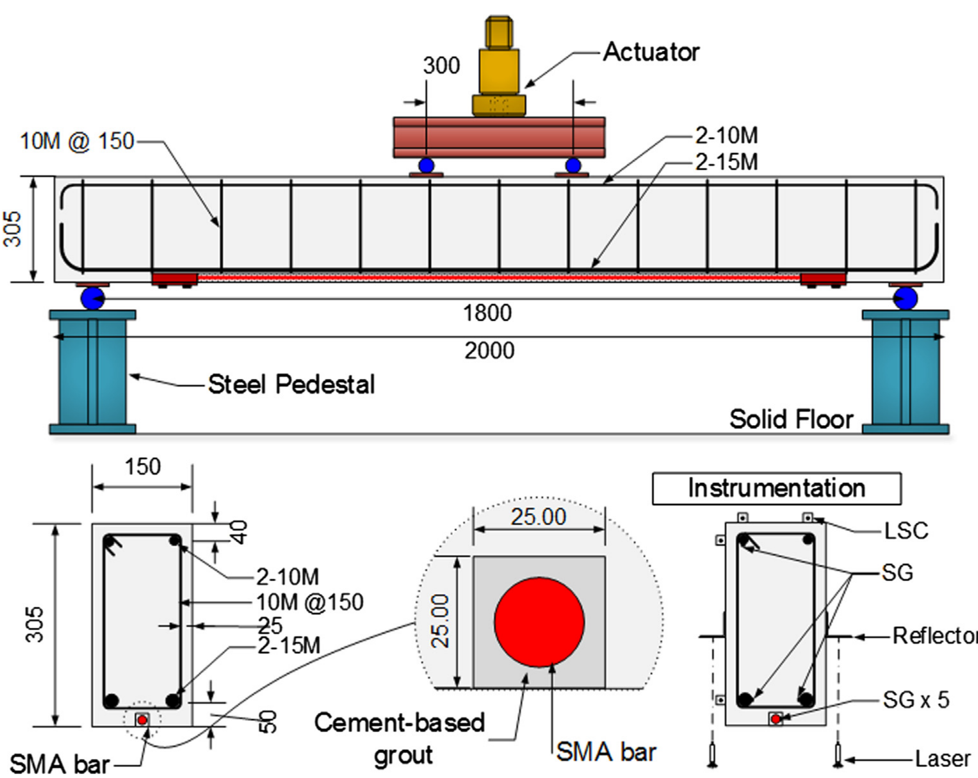

Fig. 1. Typical geometric details, the instrumentation details, and loading setup (not to scale, all dimensions are in mm).