LOCALIZED PRESTRESSING SYSTEM FOR CONCRETE CROSSTIES USING SHAPE MEMORY ALLOYS

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ABSTRACT

One of the limitations of conventional pretensioned systems is that the prestressing is applied to the entire member even at the regions where prestressing is unnecessary. A new local prestressing system is proposed by adjusting the wire arrangements using wires made of shape memory alloys (SMAs). The proposed system applies prestressing only to the localized region of interest. This paper presents a proof-of-concept experimental study of the new prestressing scheme. Three small scale concrete crosstie specimens with different SMA wire profiles are tested. Digital Image Correlation (DIC) and strain gauges are used to monitor strain distribution along the specimens during and after prestressing application. The results show that the proposed SMA prestressing system is effective in locally prestressing the regions where concrete cracking is expected.

Keywords: Prestressed Concrete, Shape Memory Alloys, Concrete Crosstie, Localized Prestressing

INTRODUCTION

Concrete prestressing has been widely used in various structural applications, including in the production of precast concrete railroad crossties. Crossties are horizontal members in the rail track system, which support the rail transferring the load from the rail to the ballast. Although the magnitude of the vehicle load may vary, the location of the load applied to the crossties is somewhat consistent. The flexural demand of the concrete crosstie largely depends on the ballast support condition. The ideal ballast condition for the crosstie is being evenly distributed, which minimizes the moment demands on the crosstie. However, maintaining an even ballast support condition is not an easy task due to the environmental conditions and the repeated use of the track. The uneven distribution of ballast can lead to increase in the flexural demands at the center region, a phenomenon known as center binding (see Fig. 1a) or at the rail seat region (see Fig. 1b). Center binding usually occurs in a heavy-haul rail track where the bearing surface of the crosstie is not fully in contact with the ballast. The gap between the rail seat and the ballast widens over the time, and thus only the midspan is rigidly supported by the ballast (Chen et al.[1]). The wheel loads at the rail seats under center binding support condition generate a negative moment at the center section, which leads to crack development at the midspan (see Fig.1a). Similarly, the lack of rail seat support is because of a gap between the rail seat and the ballast as shown in Fig.1b.

Since crossties are typically pretensioned using straight wires, it is inevitable that the prestressing force is applied throughout the entire length of the crosstie including locations where prestressing is unnecessary such as at the crossties end zones or compressive zones. The lack of uniform support under the crosstie causes the increase in compressive stress in some parts of the crosstie that are already prestressed, which could lead to premature failure of these regions. Based on the schematics presented in Fig. 1 it is clear that ideally, crossties would require prestressing near the top fibers at the center region and near the bottom fibers at the rail seat regions. Such variation in the position and magnitude of prestressing is not feasible with conventional pretensioning systems currently used in manufacturing these crossties. This study presents solution to this problem through proposing a new local prestressing system that can apply prestressing in precast members including crossties at the locations where prestressing is needed. The proposed concept relies on the use of an emerging class of metallic materials known as shape memory alloys.

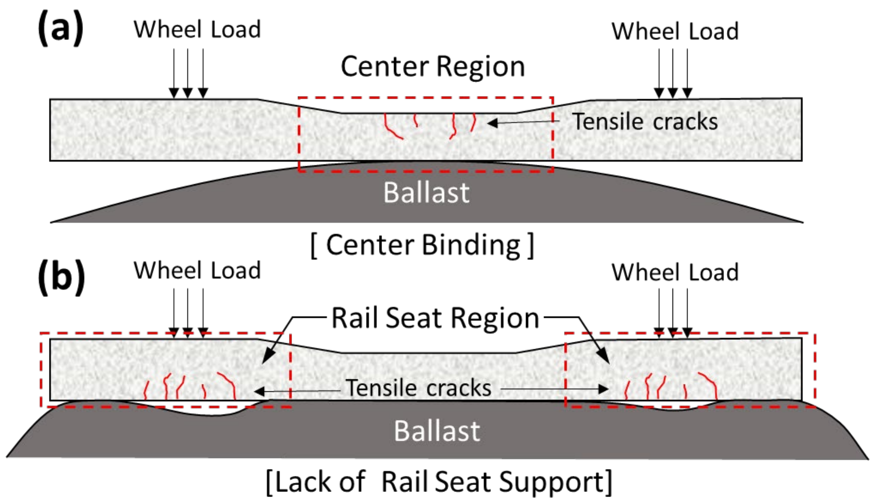

Fig. 1 Schematic representation of (a) center binding support condition, (b) lack of rail seat support condition

SHAPE MEMORY ALLOYS

Shape Memory Alloys (SMAs) are categorized as smart materials due to their unique thermo-mechanical characteristics which enables the material to recover its original shape after being excessively deformed. SMAs have been actively studied in various structural engineering applications such as active confinement of concrete columns (Andrawes et al.[2], Shin and Andrawes[3], Jung et al.[4]), vibration damping and energy dissipation (Cardone et al.[5], Shahin et al.[6], Ocel et al[7], Graesser and Cozzarelli[8]), and prestressing of concrete (Maji and Negret[9], Deng et al.[10], Czaderski et al.[11], Lee et al.[12], Shahverdi et al.[13], Rojob and El-Hacha[14]).

The phenomenon of shape memory effect (SME), which attracted the attention of many researchers is observed in SMAs due to a microstructural phase transformation that is triggered by temperature. Once the deformed SMAs is heated, the phase transformation from Martensite to Austenite is activated. During the transformation, if the SMA is not constrained, it will recover its original shape. However, if the SMA is constrained, recovery stress, σ_{rec}, is generated internally within the alloy. In the proposed prestressing application, the recovery stress induced due to SME is utilized to apply the prestressing force by anchoring both ends of the SMA reinforcement to the concrete, preventing the SMA from recovering its shape.

The SMA used in the study is NiTiNb. The chemical composition of the material is Ni-55-Ti-36-Nb-9, % by weight. The recovery stress of the NiTiNb is 79.77kips. After the prestressing is applied, NiTiNb behaves nonlinearly under tensile loads as shown in Fig. 2. (Zhao and Andrawes[15]). The ultimate stress of the material was 184.35ksi and the corresponding strain was 21.88%.

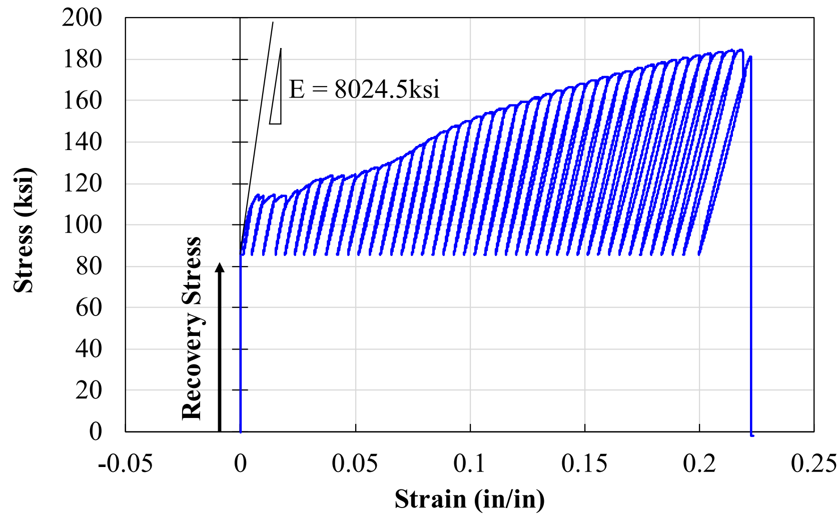

Fig. 2 Stress vs strain relationship of the NiTiNb wire (Zhao and Andrawes[15])

ADVANTAGES OF PROPOSED PRESTRESSING SYSTEM

In this study, a new localized prestressing system is proposed using SMA reinforcement. In the new system, the prestressing force is exerted using the recovery stress induced from the shape memory effect of the SMA. The SMA reinforcement is placed in the forms before casting the concrete at the designated locations where prestressing is needed. After the concrete is set, prestressing force is then activated by heating the SMA reinforcement. The advantages of the proposed prestressing system in crossties are: First, the proposed system can control end-splitting cracks, which are mainly caused by excessive stress concentration, by reducing or eliminating the prestress applied at the end zones.

Second, prestressing force can be applied with different eccentricity and magnitude at different sections along the prestressed member depending on the demand at each section (see Fig. 3). The prestressing force can be adjusted by increasing or decreasing the cross-sectional area of the SMA reinforcement used in the section. In conventional prestressing system, the prestressing force is constant throughout the length of the member (not considering prestress losses), thus the maximum required prestressing stress is applied to the entire member, which is often unnecessary. For example, in crosstie application, ideally, the required magnitude and eccentricity of prestressing force at the rail seat sections are different from that at the center section (see Fig. 3). The proposed system can apply different magnitude of prestress at the rail seat and the center sections.

Third, it is possible to alter the reinforcement arrangement and profile along the prestressed member length with much less labor and hardware compared to conventional prestressing. This is particularly needed in the case where the prestressed member is subjected to moment reversal such as in continuous beams. Using the proposed SMA prestressing system in such case is relatively simple and can be achieved by bending the SMA reinforcements to the desired shape.

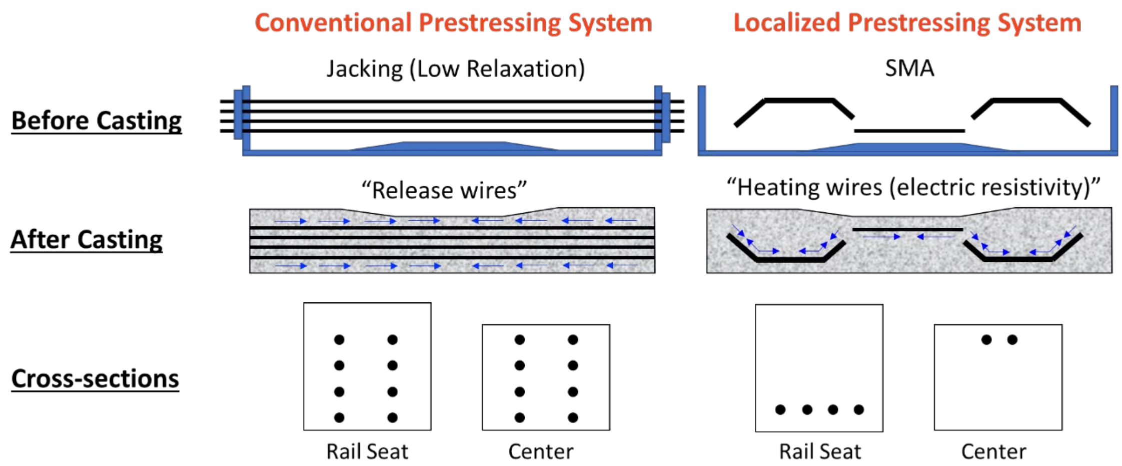

Fig. 3 Comparison of conventional prestressing system and proposed localized prestressing system

EXPERIMENTAL STUDY

The objective of this study was to prove the feasibility of the proposed localized prestressing using SMA reinforcements in concrete crossties. To that end, small scale specimens were designed with the proposed prestressing system and activated (prestressed). During the activation of the SMA reinforcement in the specimens, the strain distribution along the surface of the specimens and strain at discrete points were measured to verify the prestressing is applied as intended. In addition, three different reinforcement profiles were explored to investigate the validity of the new concept with different reinforcement profiles.

TEST SPECIMEN DESIGN

The test specimens used in this study were scaled down to approximately 1/3 of a reference tie that was designed as per American Railway Engineering and Maintenance-of-Way Association (AREMA) design guidelines (AREMA Ch.30[16]). The elevation view of the test specimen is shown in Fig. 4. The length of the specimen is 30 inches, and the width of the section is 3 inches. The height of the rail seat section and center section are 3 inches and 2.3 inches, respectively. The SMA reinforcement used comprised 2mm diameter Nickel

Titanium Niobium (NiTiNb) wires, which based on previous studies exhibited a recovery stress of 550MPa (79.77 ksi) and a recovery force of 0.3884 kip per wire (Shin and Andrawes[3]). This recovery stress can be achieved by heating the NiTiNb wires up to a temperature of 200°C. To increase the cross-sectional area of the SMA wires, two 2mm diameter NiTiNb wires were bundled and wrapped with nylon sleeves. The nylon sleeves were used to debond the wires from the concrete as well as to insulate heat generated from the heating of the SMA wires. It can be replaced to a sheething or a plastic duct in a real construction for the future. The ends of the SMA reinforcement were bent to form a 180-degree hook for anchorage. The concrete mix was designed with a target compressive strength of 3ksi in 28days.

Separate section designs were conducted for center and rail seat sections as shown in Fig. 4. The design goal was to achieve proportional amount of stress at the extreme pre-compressed fibers after prestressing. In rail seat sections, 4 bundles of NiTiNb wires were placed at 0.5in from the bottom of the section with a spacing of 0.6in. In center sections, 3 bundles of wires were placed at 0.5 inch from the top of the section with a spacing of 0.75in. The prestressing forces and the stress induced by prestressing of the designed sections are listed in Table 1. The designed sections could achieve 77.1% and 51.7% of the bottom stress of the AREMA-based reference crossties at the rail seat and center sections, respectively.

Table. 1 Prestressing force and the stress induced by prestressing

	Symbol	Section	
		Rail seat	Center
Area of the section (in^2)	A_c	9	6.9
Total Area of SMA (in2)	A_{SMA}	0.0390	0.0292
PS force by SMA (kip)	F_{ps}	3.11	2.33
PS force by unit area (ksi)	F_{ps}/A_c	0.35	0.34
PS stress by eccentricity (ksi)	My/I	0.69	0.57
Stress at extreme fiber (ksi)	$\sigma_{extreme\ fiber}$	1.04	0.91

To explore different reinforcement profiles, three profiles were designed, namely, Straight, L-shaped, and U-shaped in specimens SP1, SP2, and SP3, respectively (Fig. 5). The rail seat region can be categorized as a "deep beam" as per ACI 318-14[17] under the rail seat positive test condition, which is prone to shear failure. The diagonal component of L-shaped and U-shaped wires were designed to reinforce the crossties in shear.

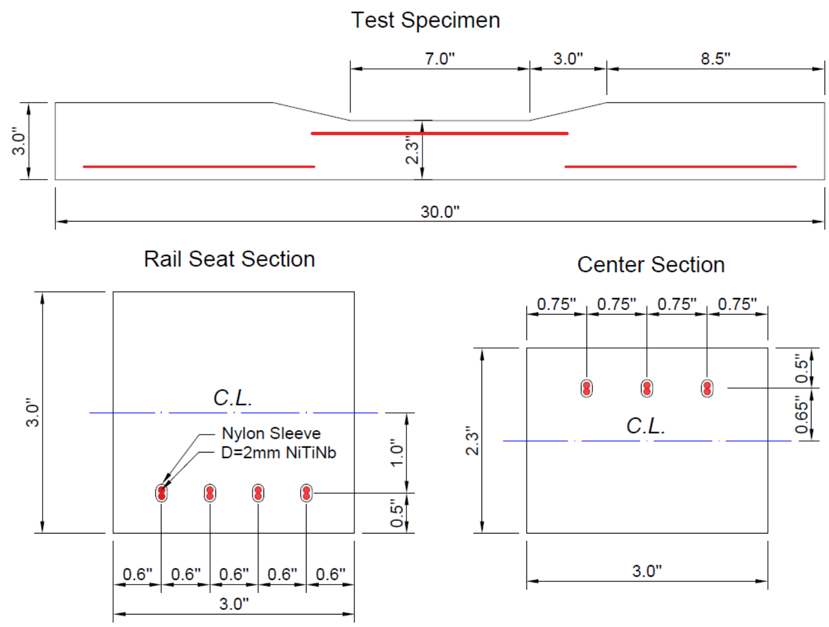

Fig. 4 Specimen dimensions and section designs

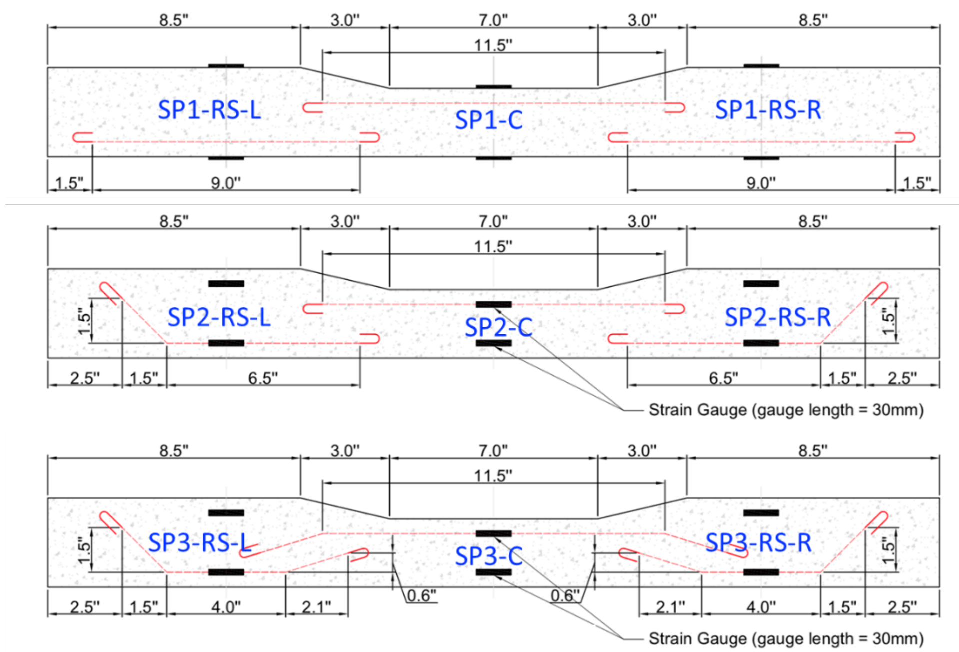

Fig. 5 Three different SMA reinforcement profiles for the tested specimens

TEST SETUP

To explore the feasibility of the proposed prestressing system, the specimen strain during and after the activation of the SMA reinforcements were monitored. Digital Image Correlation (DIC) technique was used to measure the strain distribution of the surface of the specimen. White paint was applied to the front surface of the specimen and speckle patterns were applied on top of the white paint. During the heating of the SMAs, a camera placed in front of the specimen was used to capture photos with a rate of 1.0 frame per second (see Fig.6a). The photos were post-processed using Vic2D software[18].

To measure the strain at discrete points, strain gauges were attached to the top and bottom of the specimens at both rail seat and center locations (see Fig.6a). The strain gauges were attached at the top and bottom surface in SP1 and at the same level of the prestressing wire in SP2 and SP3 (see Fig.5 and 6a). SMA prestressing activation was performed separately at left rail seat, center, and right rail seat.

Electrical resistivity was used to heat the SMA reinforcement. Copper lead wires were connected to both ends of the SMA reinforcement to form a closed circuit with DC power supply (see Fig.6a). Temperature of the wires was monitored during the heating of the SMA reinforcement. The tip of the thermo-couple was in contact with the SMA wires, penetrating through the nylon sleeve which wraps the SMA wires (see Fig.6b). The DC power supply was disconnected when the temperature reached 200°C to prevent the overheating which could possibly damage the concrete at early age.

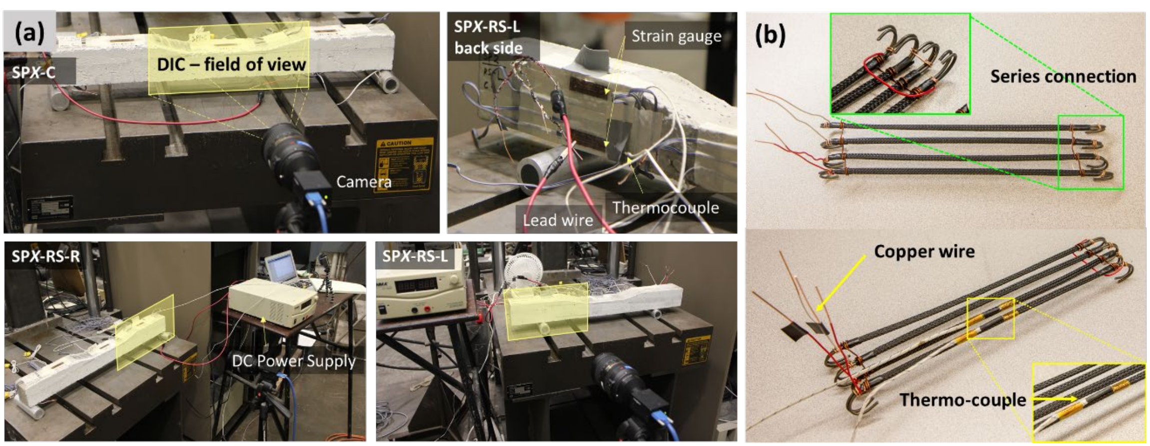

Fig. 6 (a) Test setup, (b) SMA wire assembly

TEST RESULTS

The activation of the SMA wires was done 3 days after casting. The concrete strength in 3 days was 2461.5 psi. Fig. 7 shows the temperature measured from the thermo-couple and the strains measured from the strain gauges attached to SP3-RS-L and SP3-RS-R (see Fig. 5). In the figure, the black lines with dots represent the temperature, while the blue solid lines represent the top strain and the red dotted lines represent the bottom strain of the section. It is shown that the strains at top and bottom increase in compression and tension, respectively as the temperature increases. The peak point of temperature and strain are corresponding to each other. The temperature peaks are all greater than 200 ℃ (activation temperature) which indicates that the SMA reinforcement was fully activated. The two peaks in the temperature curve are due to the fact that the SMA wires were heated sequentially (two wire bundles at a time).

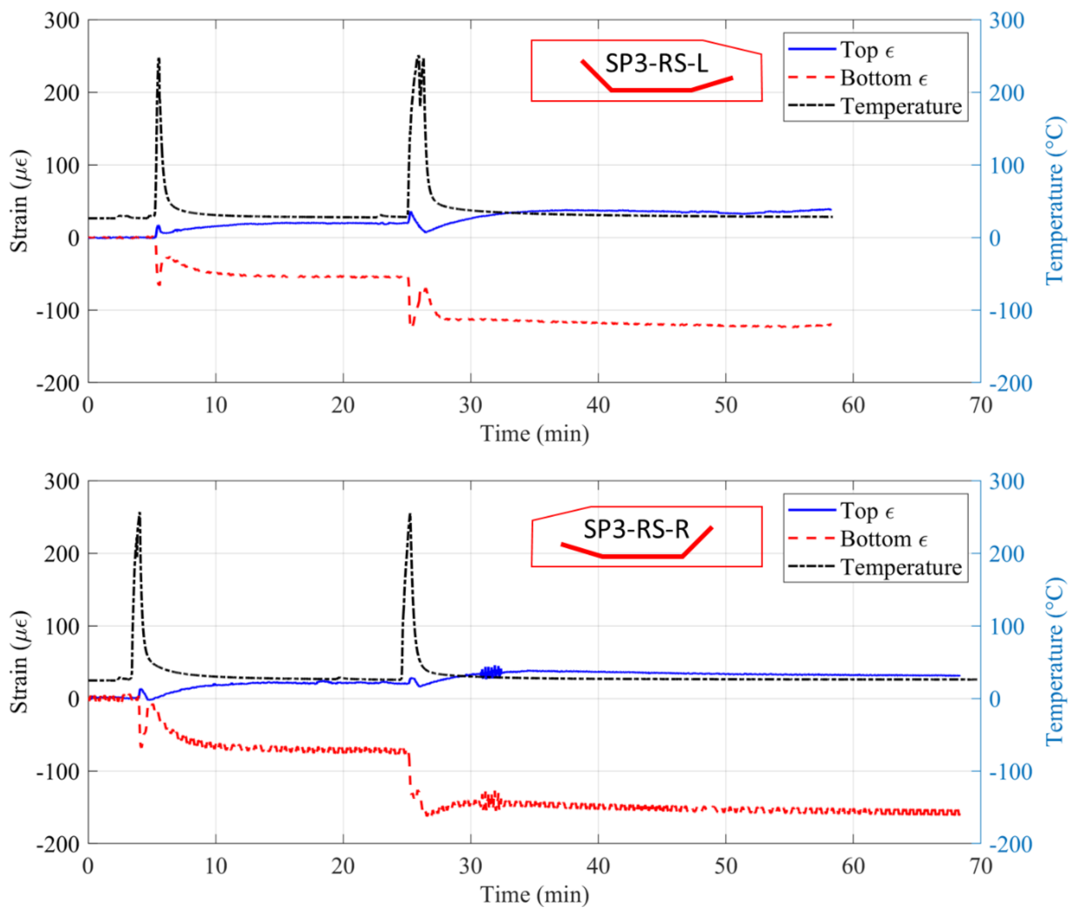

Fig.7 Time vs. strain and temperature of specimens SP3-RS-L and SP3-RS-R

Fig. 8 shows the DIC axial strain distribution of specimen SP1 after activation. The contour map is post-processed with DIC software, Vic2D[18]. The purple color represents the highest compressive strain and the red represents the highest tensile strain. It is observed that the bottom fibers of the rail seat sections and the top fibers of the center section is in compression.

This stress state matches the ideal target state of stress due to prestressing that was discussed earlier for crossties.

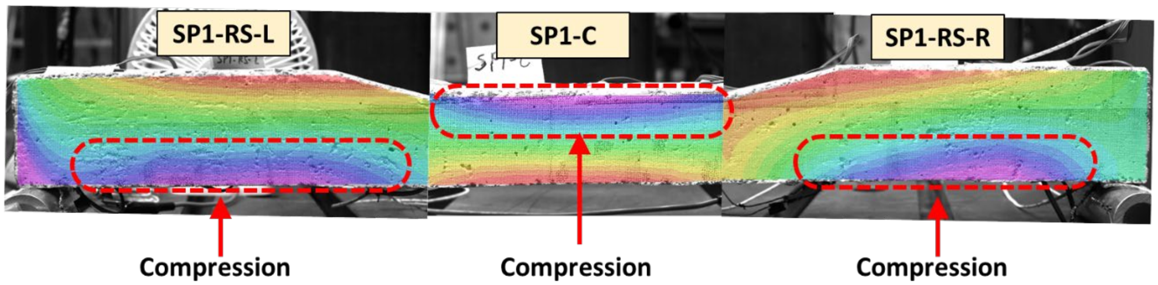

Fig. 8 Contour map of the axial (horizontal) strain distribution after activation of SP1.

Fig. 9 shows the DIC shear strain distribution along the surface of the section after activation of SP1 and SP3. The sign convention of the shear stress is shown in the bottom right corner of the figure. The top row of the figure shows specimens SP1-RS-L and SP1-RS-R which are reinforced with linear SMA reinforcement and the bottom row shows specimens SP3-RS-L and SP3-RS-R, which are reinforced with U-shaped SMA reinforcement (see Fig. 5). SP3 shows the shear stress concentration near the diagonal legs, whereas SP1 does not seem to have such stress concentration. This proves that the U-shaped reinforcement was effective in applying shear stress to the location where the shear failure is predicted.

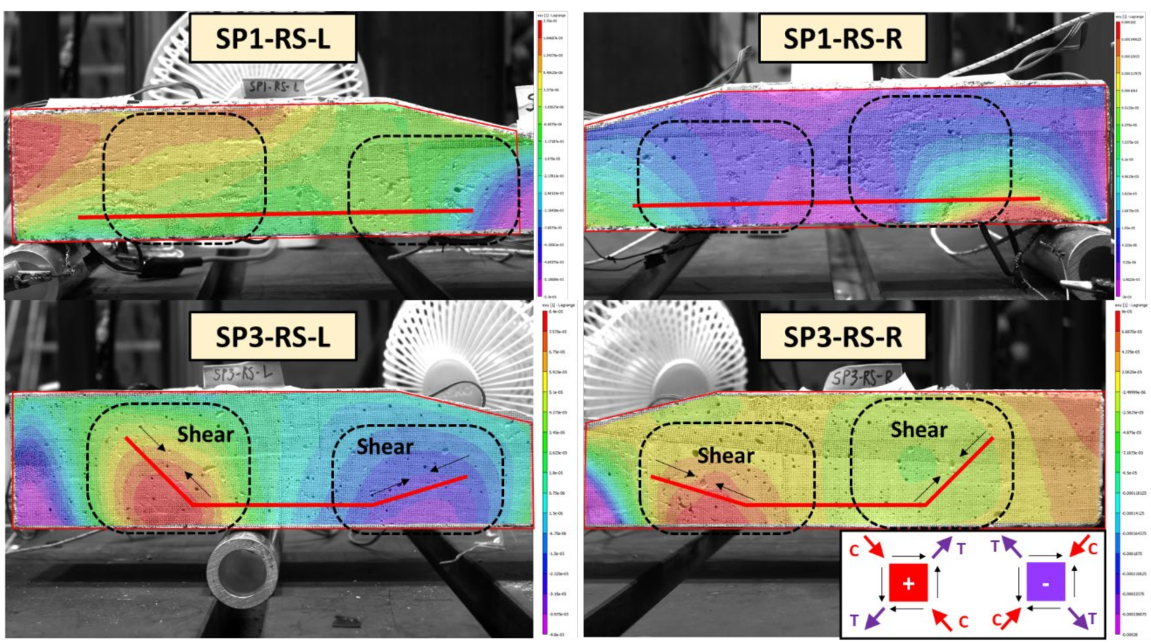

Fig. 9 Contour map of the shear (diagonal) strain distribution after activation of SP1 vs SP3

CONCLUSIONS

This paper presented a proof-of-concept study on a new localized prestressing system that was proposed for prestressing crossties. The new system comprised of NiTiNb SMA wires. The proposed system exploits the recovery stress induced by the shape memory effect of SMA to apply the prestressing force. Unbonded SMA reinforcement was anchored in concrete using 180-degree hook at both ends. Three small-scale specimens were designed and fabricated based on a reference crosstie that was designed as per AREMA recommendations. Different prestressing force and eccentricity were applied at the rail seat and center regions of the tested specimens. Furthermore, three different reinforcement profiles were investigated. The DIC strain distributions and the strain gauges output both show that the proposed SMA prestressing system is effective in applying prestressing force at rail seat and center regions of the crosstie with different magnitudes as designed. Further, studies are underway to investigate the flexural and shear behaviors of the SMA prestressed specimens under externally applied loads.

AKNOWLEDGEMNTS
The authors acknowledge the financial support provided for this study by the Rail Safety IDEA program under project No. 33.

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