

Experimental Study on Prestressed CFRP-reinforced Aluminum Alloy Bridge Panel Based on Shape Memory Alloys

Zihan Li^{1,a}, Qilin Zhao^{1,b}, Yonglong Zhu^{2,c}

¹College of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 211816, China

^a201761100747@njtech.edu.cn, ^bZhaohsq1919@163.com, ^c2244671096@qq.com

Abstract. In order to strengthen aluminum alloy bridge panels, a CFRP (Carbon Fibre Reinforced Plastics) plate is tensioned under the bottom plate to exert prestress. Installing the tensioning device under narrow bottom plates of bridge panels via traditional prestressing method is difficult; therefore, a new prestress tensioning technology based on Shape Memory Alloy (SMA) is employed to efficiently apply the prestress. The tensioning and anchorage device used in prestressing technology has been designed and manufactured. A tensile stress of 360Mpa was applied to the CFRP plate with the tensioning and anchorage device and then, load-bearing tests were performed on prestressed reinforced aluminum alloy and unreinforced bridge panels, respectively. Experimental results showed that the proposed CFRP prestressing technology was feasible and verified the application possibility of SMA as a prestress device in practical engineering. The new technology ensured that the desired prestress value was applied to aluminum alloy bridge panel and the strength and stiffness of aluminum alloy bridge panels reinforced with the proposed technology were significantly improved.

Keywords: Shape memory alloy; Aluminum alloy; Prestress; Pre-loaded tooth

1. Introduction

Aluminum alloy has the advantages of lightweight, low price and corrosion resistance. Bridge panels and beams made of aluminum alloy can effectively decrease the weight and improve the efficiency of emergency bridge erection process[1,2]. However, in the research of a large span assembled emergency bridges composed of aluminum alloy bridge panels and high strength steel-composite truss bearing beams, we found that the specifications of the existing aluminum alloy plates in the market are less and low elastic modulus of aluminum alloy results in low working stress state of aluminum alloy bridge panels with deformation control requirements; i.e., the strength of the material is not fully exploited. Previous studies have shown that application of prestressed CFRP plates to reinforce aluminum alloy bridge panels could improve their strength, stiffness and bearing capacity. For example, Zheng[3] found that the application of prestressed CFRP to strengthen aluminum alloy trusses enhanced the bearing capacity of the structure more than two times as high. Zhu et al.[4] used CFRP bars to apply prestress to aluminum alloy I-beams and improved bending stiffness and bearing capacity of the structure by 25%. Therefore, while developing emergency bridges, we suggested the application of prestressed carbon fiber plates to strengthen the existing aluminum alloy profiles to give full play to material strength and further reduce dead weight[5].

The first externally prestressed CFRP system was invented by Andra et al.[6] in collaboration with the university of Leipzig, Germany, and was fully tested at EMPA Institute in Switzerland. The developed device was composed of a ceiling platform embedded and cemented into concrete grooves, an anchoring device connected to the end of a CFRP and a tensioning tool. Micro hydraulic jack was pressurized between tensioning tool and anchorage device, thus jack-up anchorage device and tensioned CFRP. In recent years, the study of external prestressing system has been perfected. Regardless of the material being CFRP cloth[7], plate[8], sheet[9] or bar[10], new prestressed tension techniques have been developed. However, the carbon fiber plate prestressed tensioning device in previous studies was inseparable from tensioning tools and jacks. The processes of loading and unloading tensioning tools and jacks are time-consuming and due to

limited size of jacks, it is difficult to install the device in a narrow places such as the bottom plate of a Π -beam.

Shape memory alloys (SMAs) have shape memory effect. Residual strain is generated through the application of deformation to SMA at low temperature, restrain both ends, and then heat them above a certain temperature. This way, the recovery of SMA deformation is limited, resulting in the generation of recovery stress in the inner part of SMA. Therefore, shape memory effect could be applied to convert temperature change into stress, which allows SMA to drive a variety of devices. SMA actuators designed based on the shape memory effect of SMA have the advantages of high power to mass ratio, simple structure, and no noise[11]. SMA actuators have replaced traditional actuators such as hydraulic jacks, pneumatic jacks and electric motors in intelligent structures[12-15]. In civil engineering, SMA is mainly applied to strengthen structures. Maji and Negret[16] used SMA wire to provide prestress in concrete members. Steel strands made of NiTi SMA wires were stretched beyond their plastic limits and then embedded in M-type concrete beams. Using electric heating, NiTi SMA wires experienced high shrinkage strains to produce huge prestress in concrete. Lee and Kim[17] fabricated shape memory alloy hybrid composite (SMAHC) beams embedded with SMA and beam bending was controlled by electrically heating SMA. ZHANG, et al.[18] applied SMAHC plates to strengthen reinforced concrete beams where the prestress level of SMAHC was effectively controlled by controlling the pre-strain and temperature of SMA.

It was seen from the above observations that, due to their shape memory property, SMAs could be used to apply prestress to beams. We also invented a rapid prestress application technology based on SMA using their shape memory effect[19]. This technology has the advantages of no lack of need for installing heavy jacks and the possibility of the application of prestress on narrow bottom plates. It is especially suitable for the reinforcement of aluminum alloy bridge panels with limited width of bottom plate. Therefore, this paper introduces the operation process of the above technology to tension CFRP plates and apply prestress to aluminum alloy bridge panels. The experimental results showed that this technology could not only apply the expected prestress to bridge panels, but also reliably anchor the reinforced prestressed carbon fiber plates on the narrow bottom plates, which met the designed bearing capacity requirements.

2. New Prestressed Carbon Fiber Tensioning Anchorage Technology

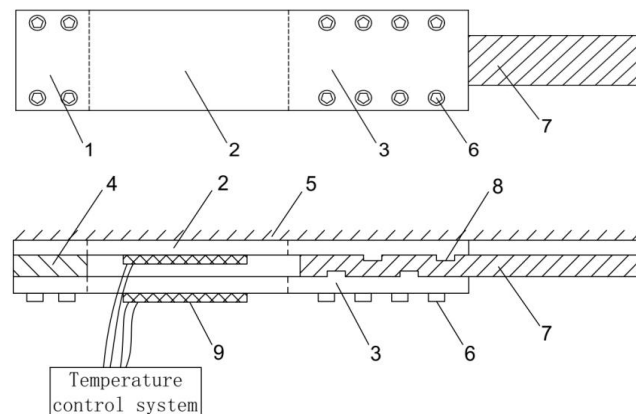
The traditional CFRP plate tensioning devices were composed of three independent components: anchor, support and tensioning tool, which not only had several assembling steps, but also required the removal of tensioning tool after the completion of tensioning. Moreover, traditional prestressing technology was limited by the sizes of tensioning tool and jack and it was difficult to install tensioning device on narrow plates. The aluminum alloy bridge panel required to apply prestress is shown in Figures 1 and 4. The width of the bottom plate was only 40 mm and the bearing capacity of the small jack adapted to this size was only 50kN. Therefore, the tensile stress applied to CFRP plate was extremely limited.



Figure 1 Aluminum alloy bridge panel

The structural bottom and side views of the proposed tensioning anchorage device based on SMA developed by our research group are presented in Figure 2. The device was simple, mainly consisting of two SMA plates and a steel plate. Along length direction, the two SMA plates could be subdivided into anchor end (1), which was fixed to beam body by bolt group, deformed part (2), which was applied to generate deformation recovery by heating, and tooth end (3), which was employed to anchor CFRP plate. Also, there was a steel spacer (4) between the two left-most SMA plates with the same thickness as the CFRP plate to be tensioned. This part was used to fill the end gap of the two SMA plates and facilitate the effective anchorage of the two SMA plates to beam body. The tooth end of the device was connected through preload tooth connection technology with a CFRP plate with the same end opening teeth. SMA and CFRP were meshed through interlocking teeth and longitudinal preload was applied to CFRP through pre-tightening bolt to improve the interlaminar shear strength and friction of CFRP contact surface and obtain high bearing capacity. Research showed that the connection efficiency of preloaded tooth connection was much higher than those of glue and bolt connections[20,21].

In the proposed CFRP tensioning anchorage device, SMA plate was employed as both tensioning anchor and tensioning end support, which realized the combination of tensioning anchor, tensioning end support and tensioning tool, greatly simplifying installation process. Since in this technology there was no need to install tensioning tools and jacks, device size could be designed to be very small. Figure 3 shows that the new tensioning anchorage device was anchored to the bottom plates of the aluminum alloy bridge panels. It could be seen that the new tensioning anchorage technology was suitable for narrow plates. Due to the above advantages, the SMA-based tensioning anchorage technology was adopted to apply prestress in this paper.



- 1- Anchorage end of SMA plate; 2-SMA plate deformation part;
3-SMA tooth end; 4-steel spacer;5- bridge panel; 6- connecting bolts;
7-CFRP plate; 8- preload tooth joint; 9- heating band.

Figure 2 Diagram of prestressed tensioning anchorage device for CFRP based on SMA



Figure 3 Prestressed tensioning anchorage device for CFRP

3. Trial Overview

3.1 Specimen Fabrication

The aluminum alloy bridge panel employed in this research was selected according to the existing specifications in the market and the selected material was 6061-T6 aluminum alloy. Figure 4 shows the cross section of the bridge panel. As was seen in the figure, the cross section of bridge panel was similar in Π shape, a top plate was connected to three webs, each web had a trapezoidal rib on its top and was connected to a bottom plate. The total length of the bridge panel was 5m and was erected on two beams 4 m apart from each other. The height of the bridge panel was 140 mm and the width and thickness of top plate were 355 mm and 7 mm, respectively. The thickness of web was 5mm. The three webs were symmetrically distributed around section midline and the distance between their axes was 120 mm. also, the bottom plate was 6 mm thick and 40 mm wide and ribs were 12 mm high, 12 mm wide on the top, and 15 mm wide below. A carbon fiber plate with length 3700 mm, width 32 mm and thickness 5 mm was anchored under the bottom plate in the middle of aluminum alloy bridge panel. The performance parameters of the bridge panel and carbon fiber plate along the three directions are given in Table 1, where prestressing was applied along Z direction.

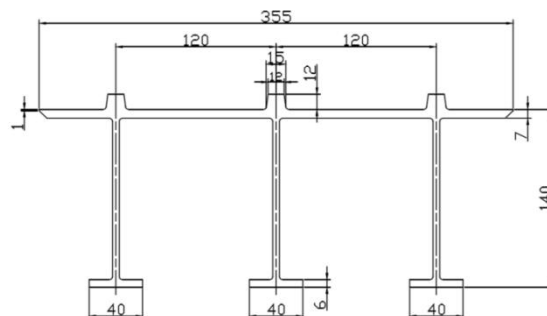


Figure 4 Section diagram of bridge panel

Table 1 bridge panel and cfrp material parameters table

Material type	E_x (Gpa)	E_y (Gpa)	E_z (Gpa)	V_{xy}	V_{yz}	V_{xz}
CFRP	10.3	10.3	150	0.35	0.03	0.03
Aluminum alloy	70	70	70	0.42	0.42	0.42

The tensioning device was consisted of two pre-machined NiTi SMA plates and two steel spacers, which were 2.5 and 4.5 mm thick, respectively. The two NiTi SMA plates were 62 mm wide and 8 mm thick and the initial length of the deformed part was 400 mm. The deformed part of NiTi SMA plate was pre-stretched to produce residual strain of 5.5%. Bolt holes were drilled in anchorage end to mount bolts to connect to beam body Tooth joint was milled out at tooth end and bolt hole was drilled to connect carbon fiber plate through the tooth and pre-tightening bolt. Grooves were machined at both carbon fiber plate ends to connect to the tooth end of SMA plate. Similarly, two steel plates with similar teeth were employed as anchoring devices to connect the other end of the carbon fiber plate. SMA tensioning and steel anchoring devices were connected with beam bottom plate and carbon fiber plate. The tensioning and anchoring devices after connection are presented in Figures 5a and 5b.

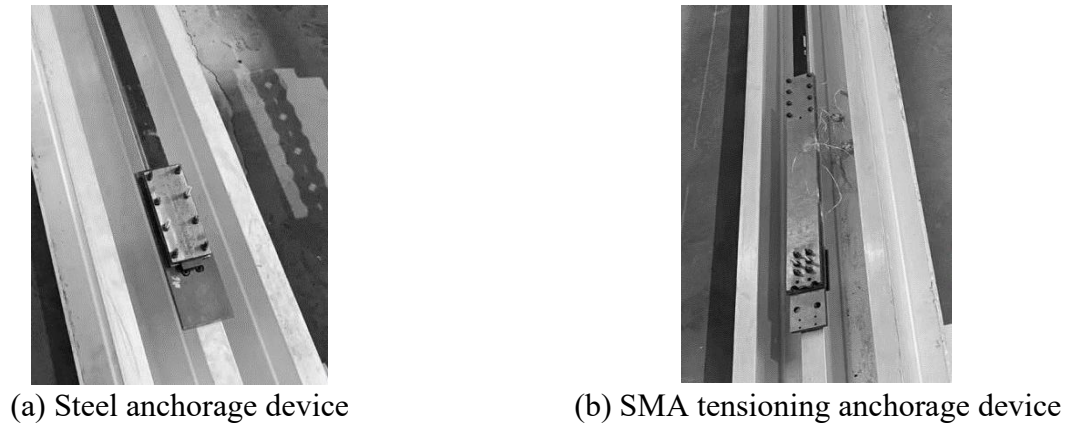


Figure 5 Anchorage and tensioning anchorage devices

3.2 Prestress Application Experiment

Heating plate and temperature control device were installed and patch type thermocouple external temperature control device was applied to measure the temperatures of the upper and lower SMA plates in real time. The real-time strain of CFRP plate was measured using a strain gauge. Installation of experimental measurement points is illustrated in Figure 6. We employed SMA-based tensioning anchorage technology to tension CFRP plates. Firstly, a heating plate with external temperature control device, as presented in Figure 7, was attached to the surface of the deformed parts of the two SMA plates. Then, power was on and temperature control device was adjusted to heat SMA plate to above phase transition temperature (90°C in this experiment). Since residual strain had been generated in the deformed part of SMA in advance by stretching, SMA underwent phase transition and produced recovery deformation at high temperatures. The tooth connection of tooth end drove the CFRP plate to generate tension, thereby applying prestress to aluminum bridge panels. SMA heating process is presented in Figure 8. The strains of SMA and CFRP plates, as well as the temperature of SMA plate were measured in real time. When the strains of SMA and CFRP plates were not changed, heating was stopped and experiment was completed after the device was cooled.

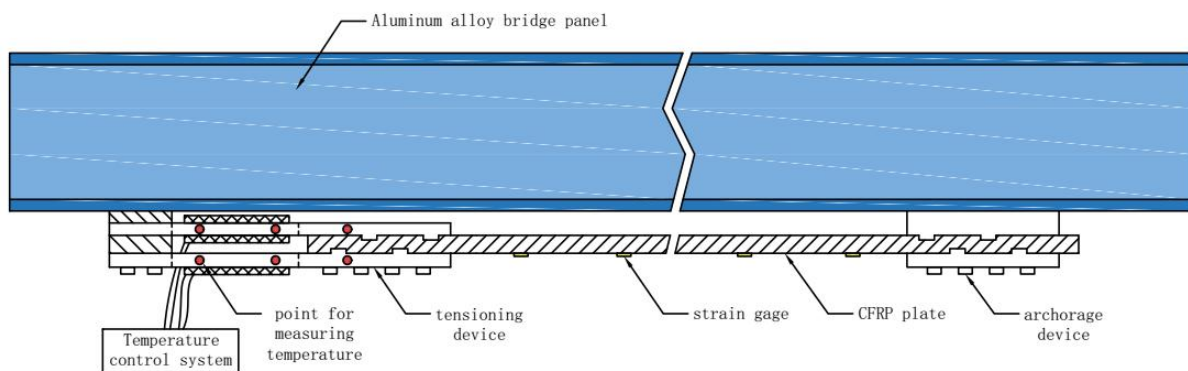


Figure 6 Layout of the experimental device



Figure 7 Heating band and temperature control device

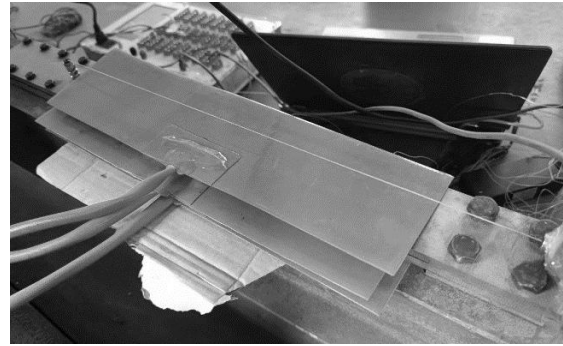


Figure 8 Heating of SMA

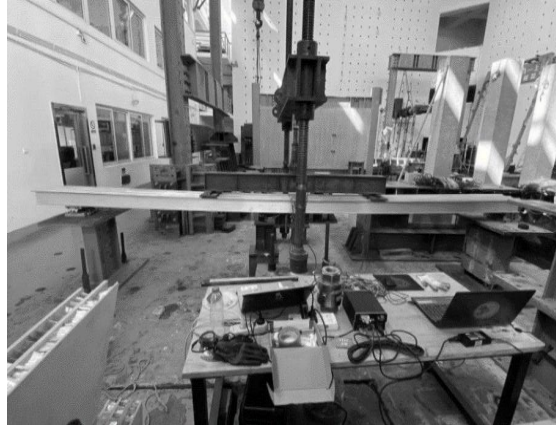
3.3 Prestress Application Experiment Load Bearing Experiment of Bridge Panel

We applied four-point bending experiment on bridge panels. Pre-stressed and unstrengthened aluminum alloy bridge panels were adopted for comparison experiments. Simply supported bridge panel was erected on two supports 4500 mm apart from each other. Two steel blocks 1800 mm apart from each other were placed axisymmetrically on the bridge panel to simulate wheel load, a distribution beam was placed on blocks, vertical concentrated force was applied to the distribution beam by lifting 20T hydraulic jack, and the middle part of the bridge panel was purely bent to simulate vehicle load. The loading of the aluminum alloy bridge panel is illustrated in Figure 9a and that of aluminum alloy bridge panel strengthened by prestressed CFRP plate is shown in Figure 9b.

According to the findings of this paper, the mid-span deflection of bridge panel under loading, the compressive strain of mid-span upper plate, the tensile strain of mid-span bottom plate, web shear strain at load and the shear strain at support were measured in the experiment. In addition, for prestressed bridge panels, the tensile strain of CFRP plate was also measured. The strain gauge measuring point arrangement as follows: the axial arrangement across the upper three strain gauge, the axial arrangement across the web in 3 strain gauge, across the three lower along the axial arrangement in strain gauge, load at the top of the web to x, xy, y direction arrangement 3 strain gauge, the joints of the bottom of the web to x, xy, y direction arrangement 3 strain gauge. In addition, for prestressed bridge panels, strain gauges had to be axially pasted on CFRP plates. In addition to strain gauges, it was also necessary to install pressure sensors to measure the jacking force applied by the jack and telescopic displacement meters at the bottom plate in the span of the bridge panel to measure deflection variations. The arrangement of measuring points is shown in Figure 10. The jack was lifted and the bridge panel was loaded step by step from free state until the load reached 90 kN.



(a) Four-point bending loading of aluminum alloy bridge panel



(b) four-point bending loading of prestressed aluminum alloy bridge panel

Figure 9 Four-point bending of aluminum alloy bridge panel and prestressed aluminum alloy panel

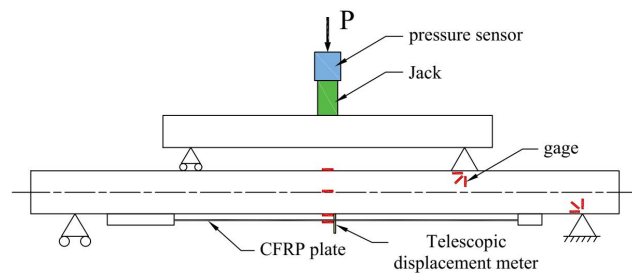


Figure 10 Arrangement of measuring points on bridge panel

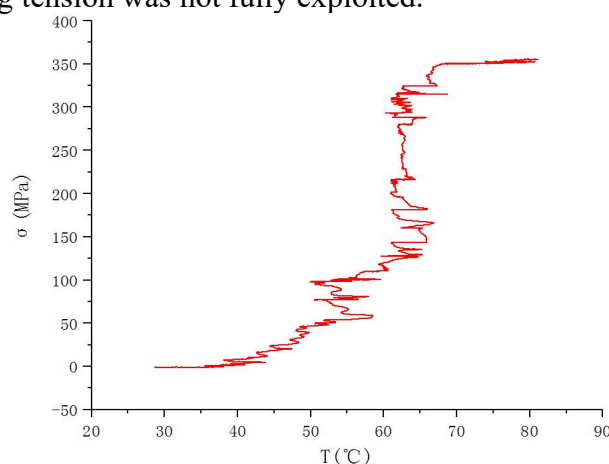
4. Experimental Results

4.1 Prestress Application Test

Tension stress was calculated according to the measured strain and elastic modulus of CFRP plates and the temperature-stress curve of NiTi SMA plate was drawn, as presented in Figure 11. It was seen that when temperature reached the transformation temperature of NiTi SMA (about 51 °C), the stress of CFRP plate was greatly increased, which proved that austenite transformation began inside NiTi SMA plate and recovery occurred. Between 51 °C and 67 °C, the tensile stress of CFRP plate was sharply increased indicating that phase transformation process was the most significant and SMA recovery rate was also high. Above 67 °C, the increase rate of strain slowed down and the phase transformation of the alloy was basically finished. As temperature continued to increase, the internal stress of CFRP plate was not further increased. Finally, the maximum tensile stress in CFRP plate was found to be 360 MPa, which meant that the prestress of 360 MPa was applied to the aluminum alloy bridge panel. In addition to preparation of specimens for subsequent load-bearing experiments, this test also proved that prestressing technology based on SMA was practical and feasible.

Due to higher cross-sectional areas of SMA plates and the fact that electric heating piece was not perfectly attached to the surface of SMA plate, SMA was unevenly heated. In order to make two SMA pieces response relatively uniformly in the experiment, the temperature and position of the heating plate were adjusted in real time. If temperature difference between different positions was too high, part of the heating plate could even be removed for a period of time. This resulted in discontinuous variations of test temperature over time and large fluctuations of stress-temperature and strain-temperature curves in the node of phase transition temperature. In addition, the residual strains applied to the deformed parts of two NiTi SMA plates in tensioning anchorage device in this experiment was only 5.5%, which did not reach the limit residual strain of about 10% for the material. Therefore, the tensile stress applied by the two NiTi SMA plates was not very high and the

advantage of SMA heating tension was not fully exploited.



4.2 Unit Load Bearing Experiment of Bridge Panel

The load-deflection curves of un-prestressed aluminum and CFRP plate prestressed aluminum alloy bridge panels are shown in Figure 12. For prestressed aluminum alloy bridge panels, the prestress was applied to bridge panel through prestress application tests of CFRP in advance, resulting in a backarch of 12 mm mid-span deflection. Therefore, for prestressed aluminum alloy bridge panels, the starting point of deflection value was set at -12 mm. It was seen that the loads of the two bridge were linearly related to deflection value. When load reached 90 kN, the deflection value of aluminum alloy bridge panel reached 38.4 mm, the downward deflection of prestressed aluminum alloy bridge panel was 30.9 mm, and the deflection value of prestressed aluminum alloy bridge panel was 18.9 mm after subtracting its backarch. It was seen that prestressed CFRP had significant strengthening effect on aluminum alloy bridge panels. The allowable deflection $L/150$ obtained from military bridge was 26.7 mm and bridge panel before strengthening was higher than allowable deflection. While maximum deflection of the reinforced bridge panel was lower than the allowable value, design requirements were met.

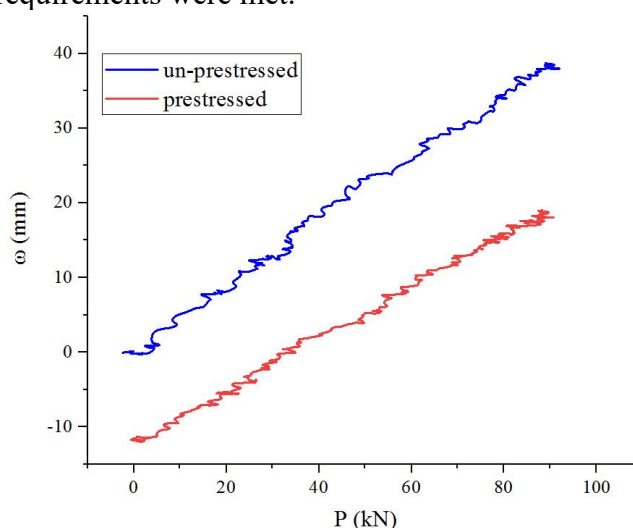


Figure 12 Deflection - pressure curve of unprestressed and prestressed aluminum alloy bridge panels

Stress at the measured point could be obtained by multiplying the experimentally measured strain by the elastic modulus of the corresponding material. When load reached 90 kN, the maximum stresses of corresponding measurement points in the two bridge panels are given in Table 4. The mid-span normal stress of prestressed bridge panel bottom plate was significantly lower than that of unstrengthened bridge panel and the normal stresses of the three bottom plates after applying prestress became 58.6, 58.2 and 70.5% of the original value, respectively. It was seen that the

prestressed CFRP plate effectively reduced the mid-span normal stress of the aluminum alloy bridge panel. The difference between the measured normal stress of the three bottom plates in the middle of the span was large, which was due to the wide bridge panel employed in this experiment. When placed on support, one side of the bottom plate pad was on the raised edge of the support, which made the transverse force of the specimen uneven. The normal stress of the upper plate corresponding to the middle web was much less than that of the two sides. This was due to the fact that only the middle bottom plate was reinforced with prestress, which significantly decreased the bending stresses of the bridge panel in the middle of the web plate and the upper plate to which it was connected; also, web position on both sides of the bending stress reduction was much smaller. The tensile stress of CFRP plate under the prestressed bridge panel was 598.03 MPa, which was significantly higher than the initial prestress of 360 MPa. This was because the bending moment generated by the vehicle increased normal stress at bottom plate and enhanced the tensile stress of the CFRP connected to bottom plate. With the increase of CFRP internal tension stress, the tension of SMA tensioning anchorage device was also increased. After the experiment, the length of the device was not changed, which proved that the device was stable and reliable.

Table 2 Maximum stress at each measuring point of un-prestressed and prestressed aluminum alloy bridge panels

Measured maximum stress /MPa	Un-prestressed aluminum alloy bridge panel	Prestressed aluminum alloy bridge panels
Bottom plate 1 mid-span normal stress	147.13	86.28
Bottom plate 2 mid-span normal stress	180.91	105.23
Bottom plate 3 mid-span normal stress	166.92	117.64
Upper plate 1 mid-span normal stress	59.16	72.39
Upper plate 2 mid-span normal stress	46.28	49.26
Upper plate 3 mid-span normal stress	52.75	63.83
Web shear stress at the support	22.68	19.48
Web shear stress at load	43.20	39.35

5. Conclusion

In this research, the feasibility of the application of SMA as a tensioning anchorage device to apply prestress to steel structures was experimentally studied. Also, the application of SMA in practical engineering was explored and prestress tensioning anchorage technology based on shape memory alloy was verified to be practical and feasible. The following conclusions were drawn:

(1) An SMA-based tensioning anchorage device was designed by using shape memory effect and was applied to strengthen aluminum alloy bridge panels, which applied 360 MPa prestress to bridge panel.

(2) Through load-bearing experiments, it was verified that the aluminum alloy bridge panel strengthened by the proposed method could bear the load of 90 kN and its strength and stiffness met the design criteria of bridge panels. At the same time, it was verified that SMA tensioning anchorage device was practical and reliable.

References

- [1] Wen Qingjie, Zheng Zhiling, "Design and Experimental Study of Aluminum Alloy Bridge Panel Section". Proceedings of 2020 Industrial Building Academic Exchange Conference (Volume 2), 2020-11-21.
- [2] TOMASZ S, "Aluminum Bridge-Past, Present and Future". Structural Engineering International, 2006, 716(4): 286-293.

- [3] Zheng Zhiling, "Research on the Bearing Capacity of Prestressed CFRP-Aluminum Alloy Truss Bridge". Xuzhou: China University of Mining and Technology, 2021.
- [4] Pengcheng Zhu et al. "Structural analyses of extruded CFRP tendon-anchor system and applications in thin-walled aluminum CFRP bridge". *Thin-Walled Structures*, 2018, 127:556-573.
- [5] Zhu Y L. "Research on prestress application technology of aluminum alloy composite bridge panel based on shape memory alloy". Nanjing: Nanjing University of Technology, 2022.
- [6] Andra, H.-P., M. Maier. "Strengthening with Bonded Prestressed CFRP Strips in post-strengthening exercises". *IABSE Congress Report*, 2015, 25 (2) : 107-105. Lucerne 2000 (1507-1514).
- [7] Deng Y et al. "Experimental and analytical investigation on flexural behaviour of RC beams strengthened with NSM CFRP prestressed concrete prisms". *Composite Structures*, 2021;257:113385.
- [8] Junhui Li, Yi Wang, et al. "Experimental study on the flexural behaviour of notched steel beams strengthened by prestressed CFRP plate with An End plate anchorage system". *Engineering Structures*, 171(2018), 29-39.
- [9] Bartosz Piątek, Tomasz Siwowski. "Development of Strip Anchoring for CFRP Strengthening System". *Lecture Notes in Civil Engineering*, v47, p323-330, 2020.
- [10] Yu Deng, Minhe Shen, Peng Zhang, et al. "Experimental and analytical studies on steel-reinforced concrete composite members with bonded prestressed CFRP tendon under eccentric tension". *Composite Structures*, Volume 271, 1 September 2021, 114124.
- [11] Jani JM, Leary M, Subic A, Gibson MA. "A review of shape memory alloy research, applications and opportunities". *Mater Design (1980-2015)* 2014; Will 78-1113.
- [12] Calkins FT, Mabe JH. "Shape memory alloy based morphing aerostructures". *J Mech Design* 2010;132 (11) : 111012.
- [13] Brailovski V, Terriault P, Georges T, Coutu D. "SMA actuators for morphing wings". *Phys Procedia*. 2010; 10:19 and 7-203.
- [14] Kang WR, Kim EH, Jeong MS, Lee I, Ahn SM. "Morphing wing mechanism using an SMA wire actuator". *Int J Aeronaut Space Sci* 2012;13 (1): 58-63.
- [15] Rim M, Kim EH, Kang WR, Lee I. "Development of a shape memory alloy wire actuator to operate a morphing wing". *J Theor Appl Mech* 2014;52 (2) : 519-31.
- [16] Maji A K, Negret I. "Smart prestressing with shape-memory alloy". *Journal of Engineering Mechanic*. 1998, 124: 1121-1128.
- [17] Sang-Hak Lee, Sang-Woo Kim. "Self-sensing-based deflection control of carbon fiber-reinforced polymer(CFRP)-based shape memory alloy hybrid composite beams". *Composite Structures*, 251 (2020), 112544.
- [18] Yafei Zhang. "Experimental study on flexural performance of SMA/FRP reinforced concrete beams". Southeast University, May 2019.
- [19] Zhu Yonglong, Li Zihan, et al. "Research on prestressed tensioning anchorage technology of composite material and bridge deck based on shape memory alloy". *Shanxi Architecture*. 2021-12.
- [20] Li F, Zhao Q L, Gao Y F, et al. "A prediction method of the failure load and failure mode for composite pre-tightened tooth connections based on the characteristic lengths". *Composite Structures*, 2016, 154: 684-693.
- [21] Deng A Z, Zhao Q L, Li F, et al. "Research on bearing capacity of single tooth to composite pre-tightened teeth connection". *Journal of Reinforced Plastics & Composites*, 2013, 32(21): 1603-1613.