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EFFECT OF CYCLIC LOADS ON SHAPE MEMORY ALLOY-BASED COMPONENT OF CABLE-STAYED BRIDGE

Shahin Zareie.
Graduate Research Assistant, EME 3204, School of Engineering, The University of British Columbia, Kelowna, BC, Canada V1V 1V7.
Shahin@alumni.ubc.ca

M. Shahria Alam
Associate Professor, EME 4225, School of Engineering, The University of British Columbia, Kelowna, BC, Canada V1V 1V7
shahria.alam@ubc.ca

Rudolf J. Seethaler
Associate Professor, EME 4225, School of Engineering, The University of British Columbia, Kelowna, BC, Canada V1V 1V7
rudolf.seethaler@ubc.ca

Abolghassem Zabihollah
Associate Professor, School of Science and Engineering, Sharif University of Technology, International Campus
zabihollah@sharif.edu

Abstract: The cable-stayed bridge is one of the most commons types of bridges. Due to the lightweight and high flexibility of cable bridges, any external cyclic loading, such as traffic loads, earthquakes, and winds, may significantly affect the functionality and the stability of the structure. Recent developments in materials and the construction technology, lead to enhance the integrity and performance of cable bridge under cyclic loadings. Therefore, in the last decades, the attraction to the cable-stayed bridge has been raised up again throughout the world.

In spite of improving the dynamic behavior and integrity of a cable bridge, the flexibility of the modern cable-stayed bridge still remains a major issue, which puts the stability at risk. Hence, the structural control systems are required to ensure the integrity and stability of the structure. Wide-ranging control systems, including passive, semi-active and active systems, have been developed to install between the pier and the deck or added to the main structure. As their weaknesses, these systems need a source of energy or are not effectively able to adjust the stability under different loading conditions.

The smart materials, particularly the shape memory alloy (SMA), are good candidates to replace with conventional materials in control systems; they increase the stability of that bridge without having disadvantages of conventional systems. SMA is a unique alloy with the ability to recover the initial shape (superelasticity) after exposing the large deformation without requiring any source of energy. It is also able

to absorb the remarkable energy of loads. Moreover, the wire (cable) is a shape suitable for cable bridges. These features make the SMA exceptional option to replace with some of the cables in the bridge to increase the integrity and enhance the performance. Therefore, SMA wires are the ideal smart element with minimum changes required in the main structures.

In order to develop the SMA-based element, its performance should be determined under the cyclic loads, as the most common applied loads to this bridge. In this study, two important characteristics: the energy absorption capacity and the recovery ability of the SMA are investigated under cyclic loads to find the differences before and after applied cyclic loads.

Keywords: Cable-stayed bridge, flexibility, Structural control systems, Shape memory alloy, Cyclic loads, Energy absorption. Superelasticity

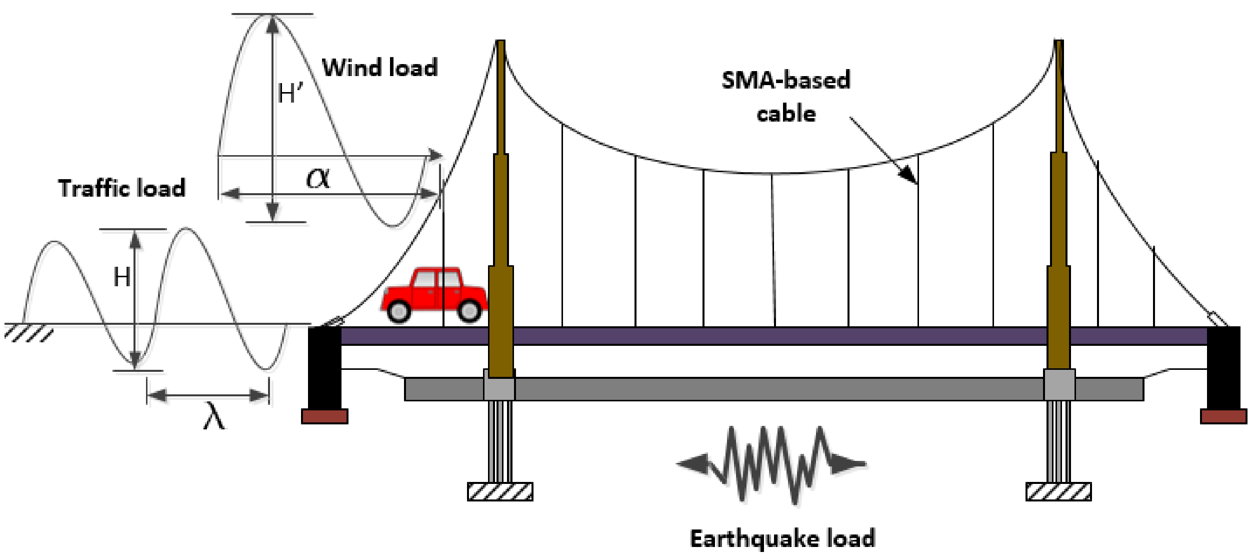

Figure 1. The schematic diagram of cable-stayed bridges equipped with SMA-based cables

1 INTRODUCTION

In spite of being the popularity of cable-stayed bridges around the world, the flexibility of these structures still remains a major issue(Ma et al. 2019; Cong, Kang, and Guo 2019). Many efforts have been made to construct those bridges with novel materials, techniques and high standard codes to improve their characteristics.

On the other hand, cable-stayed bridges are always under tough and ongoing external excitations with various amplitude and frequencies, as shown in Figure 1, including non-periodic loadings, such as hurricanes, tsunami and periodic loadings, such as day-to-day winds and traffic loads(Sharabash and Andrawes 2009; Ruangrassamee and Kawashima 2002). These loads may lead to unwanted high vibration response and become a tragic failure. In order to find the most hazardous load, the prioritization of those loads, with respect to the frequencies and the power, is the major step for design maker and designers. It helps to find the appropriate solution and protect those structures. It is clearly seen that the periodic loadings are the most frequent ones, which may remarkably influence the functionality of cable-stayed bridges.

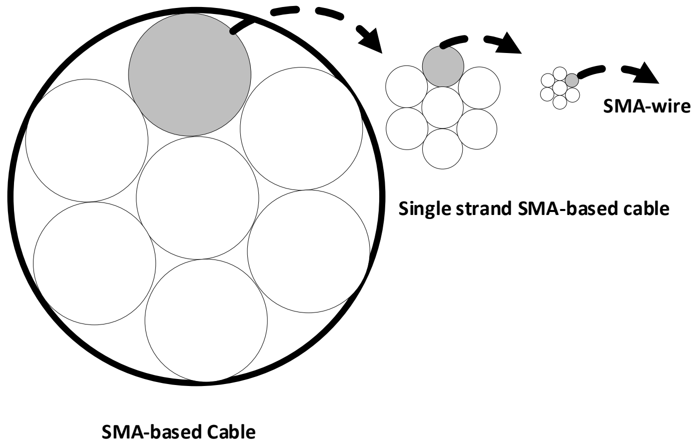

Figure 2. The SMA wire as the main component the SMA-based cable

In order to keep the stability of cable-stayed bridges, structural control systems have been integrated into the main structure or between foundation and pier of bridges. The system classified to the active, the semi-active and passive systems according to the required activation energy. Structural control systems may also be classified according to the amount of activation energy(Ghaedi et al. 2017; Jung, Spencer Jr, and Lee 2003). Due to the complexity and the remarkable high required energy, the smart structures and materials are used to develop structural control system. In a recent study, shape memory alloy (SMA)-based systems are used to enhance the dynamic behavior of the cable-stayed bridges.

The SMA is a kind of smart material with the ability to recover the initial shape after undergoing large deformation. This unique behavior comes from two properties called the superelasticity (SE) and shape memory effect (SME)(Zareie et al. 2017b). The SE happens when the external loads remove and SME occurs, if the heat applies to the SMA. In most cases, the SE is used to develop the SMA-based passive systems rather than SME, which is utilized for semi-active systems(Zareie et al. 2017a; Aryan and Ghassemieh 2017; Zheng, Dong, and Li 2018). Furthermore, SMA in both modes is capable to dissipate the energy of applied excitations. These characteristics make SMA a perfect candidate for cable-stayed bridge's protective systems to prevent any damage and keep their integrity under strong loading(H. Li, Liu, and Ou 2004; Zhou et al. 2018).

Various SMA-based systems have been developed to use in cables-stayed bridges(S. Li et al. 2018), particularly SMA-based damper system(Helbert et al. 2018; Sharabash and Andrawes 2009). The recovery ability and energy absorption capacity of these systems are a function of SMA's properties and they change with respect to the applied load. In this study, the SMA-based cable, as presented in Figure 2, is proposed to replace with the conventional cable in the cable-stayed bridge to improve its dynamic behavior. In order to find the performance of that suggested element under the tensile cyclic loads, the SMA-wire, as major elements of those systems, are experimentally tested by a loading frame machine. Changing in the residual strain and energy dissipation ability have been examined along applied cyclic loading.

2 ANALYTICAL MODELING OF SHAPE MEMORY ALLOY

To obtain the analytical modeling of SMA-wire, the constitutive law of the SMA is given by (Zuo et al. 2009):

[1] $\sigma(\varepsilon) = E(\varepsilon - \varepsilon^{T})$

where σ, E, ε, and ε^T represents stress, the Young modulus, the strain, and phase transformation strain, respectively.

The Young modulus (E) in Eq.1 is expressed by:

[2] $E = E_A + \zeta(E_M - E_A)$

where ζ denote is the phase transformation volume fraction. E_A and E_M represent Young modulus in the Austenite phase and in the Martensite phase, respectively, as shown in Figure 3.

After the applied cyclic loading, the permanent deformation might appear and it differs from the ideal hysteresis response. This changed and permanent deformation are shown in Figure 3.

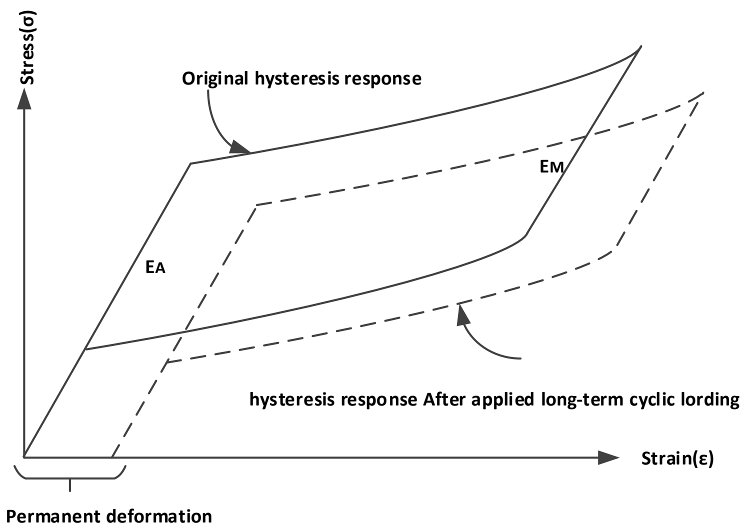

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Figure 3. The schematic diagram of the hysteresis responses after and before applied cyclic loading

2.1 Energy dissipation capacity

In order to calculate the energy dissipation numerically, the hysteresis response of the SMA specimen is discretized into n element, as illustrated in Figure 4, and the area under each element indicate the energy dissipation; the total of energy dissipation capacity is the sum of all areas. The mathematical equation is computed by (Zareie. et al. 2019):

[3] $Energy_{total} = \sum_{i=1}^{n} 0.5(F_i - F_{i-1})(D_i + D_{i-1})$

where F_i and D_i denote the amount of force and displacement in the n-th node.

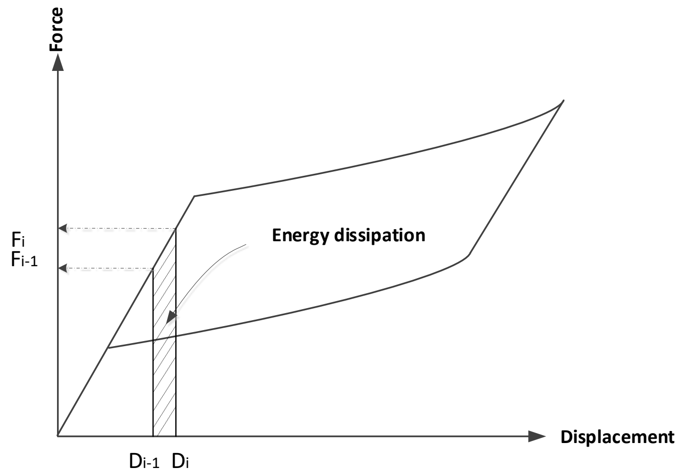

Figure 4. The methodology of energy dissipation calculation

3 EXPERIMENTAL SETUP

In order to find the hysteresis response of the SMA specimen, the servo-hydraulic loading frame machine (the MTS model 370.5) at the University of British Columbia is used. The loading frame machine is programmable to apply 500 kN. The system is equipped with sensors and control system to apply the desired loading to the specimen. The experimental setup is shown in Figure 5.

3.1 The shape memory alloy

There are different alloys of the shape memory alloys(SMAs), such as FeMn and NiTi. In the present work, NiTi manufactured by Confluent Medical Technologies company is chosen for testing. The properties of the SMA specimen is given in Table 1. The specimen 1.5 mm diameter and 560 mm length is used. The modulus of Elasticity and the Ultimate Tensile Strength(MPa) are about 41 GPa and about 1070 MPa, respectively.

Table 1. The specifications of the SMA

PROPERTIES	Value
Melting point (^oC)	1310
Density (g/cm3)	6.5
Electrical resistivity (μohm-cm)	82
Coefficient of Thermal Expansion(\\^oC)	11×10^{-6}
Modulus of Elasticity(GPa)	41
Ultimate Tensile Strength(MPa)	≥1070
Total Elongation	≥10%

To conduct an experimental test, two ends of the specimen are attached to two steel plates by nuts and plates. Each steel plate is clamped to the gripper of the MTS machine. This setup is presented in Figure 6.

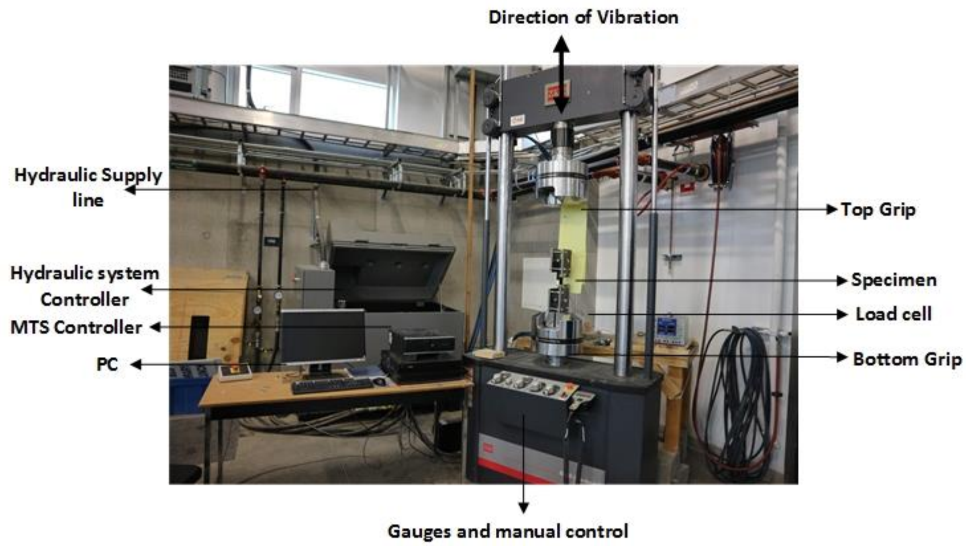

Figure 5. The MTS loading frame machine with the accessories

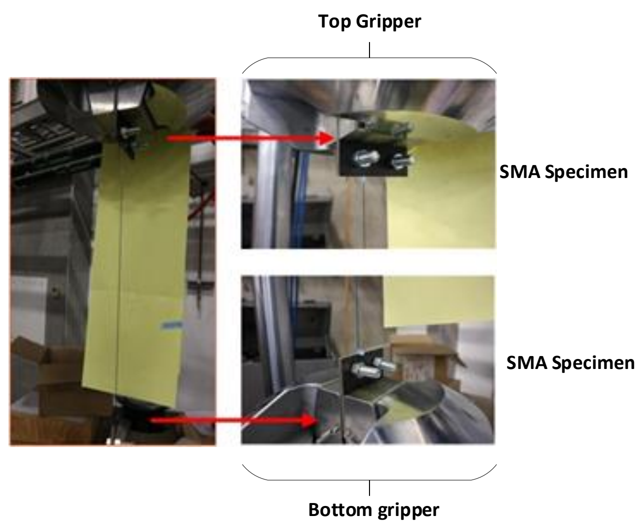

Figure 6. The experimental setup for the SMA wire

4 RESULTS

In order to obtain the hysteresis response of the SMA specimen, a loading with 1.5 mm amplitude and a 1.4s period is applied to the wire by the MTS machine, as presented in Figure 7. To simulate the long-term effect on the SMA's behavior, this loading is applied 1000 times to the specimen.

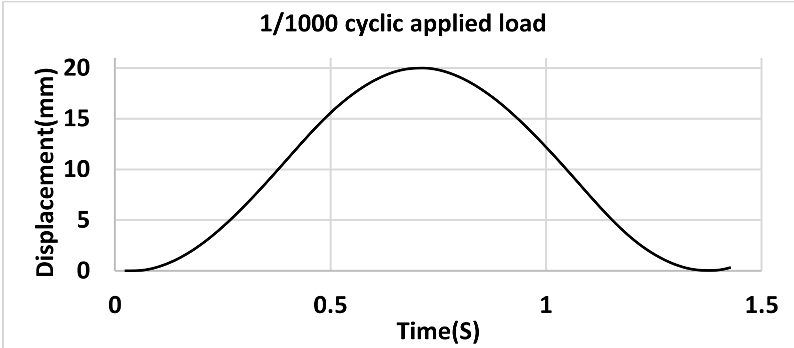

Figure 7. The cyclic loading applied by the MTS machine

The force-displacement responses are plotted after every 100 load cycles. The results are illustrated in Figure 8. It is clearly seen that the area of each response, representing the energy dissipation capacity, significantly reduce after applied cyclic loading. Furthermore, it is found that the permanent deformation shapes and increases. Due to the importance of the two parameters in the functionality of SMA-based cables, the trend of changes is studied and presented in Figure 9 and Figure 10.

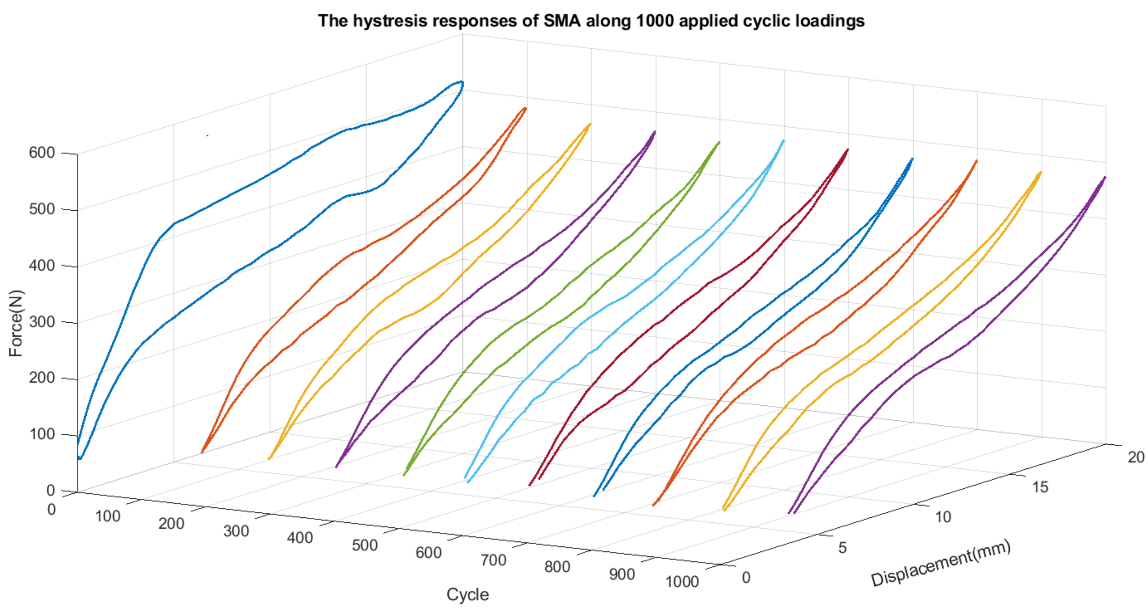

Figure 8. The hysteresis response of SMA-specimen along 1000 cycles applied by the MTS loading frame machine

The first studied parameter is the energy absorption capability of the SMA specimen. It is noted that the sharp drop occurs in the first 100 cycles, it starts from 2.29J and reaches 0.70J after applied 100 cyclic loads. Between 100 cycles to 200 cycles, it reduces gradually from 0.70J to 0.66J. After 200 cycles. it smoothly changes down from 0.66J to 0.54J under 1000 cycles. On the other hand, the major reduction is almost 67.54% of initial value occurs under 100 cycles. Between 100 to 1000 cyclic loadings, about 24.14% decrease is observed.

Estimation of the permanent deformation is the next studied parameter. An increasing about 1.5 mm (0.26 % strain) is found in the first 100 cyclic loading. Between 100 -1000 cycles, steadily increment is found from 1.5mm (0.26% strain) to 2.29 mm (0.4% strain). In other words, remarkable permanent deformation forms under 100 cycles surprisingly, then it changes up moderately.

The study shows that the long-term loadings significantly change the characteristics of the SMA-wire including the permanent deformation and the energy dissipation capacity significantly, particularly in the first 100 cyclic loadings due to the degradation in the SMA-wire. Thus, these effects should be considered.

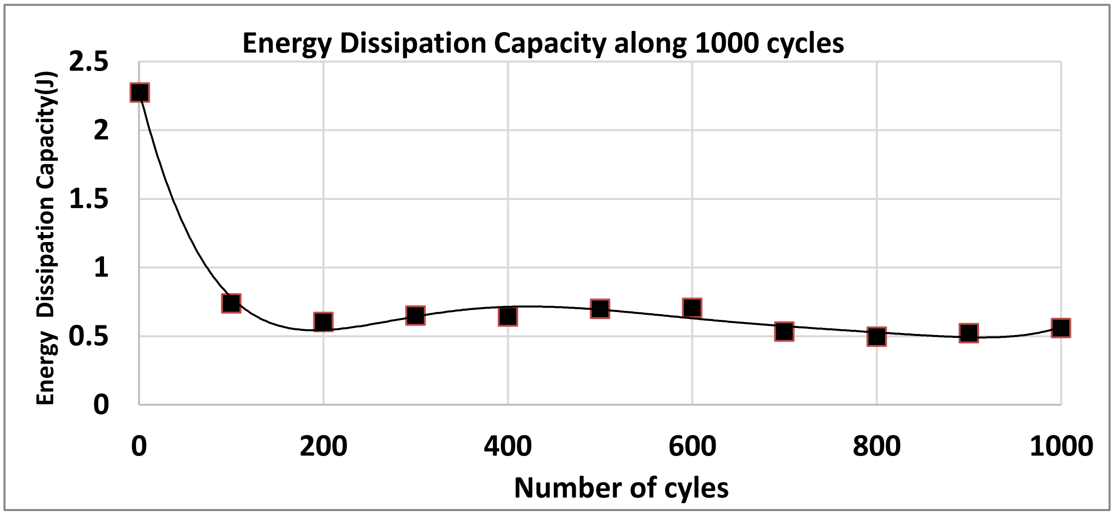

Figure 9. The effect of cycling loading on the energy dissipation capacity of the SMA-based wires

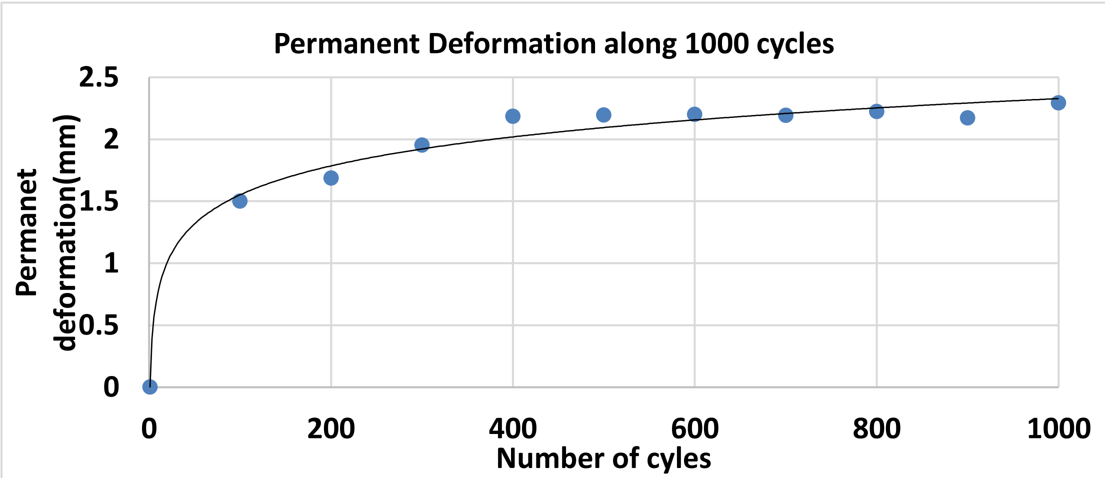

Figure 10. The effect of cycling loading on the permanent deformation of the SMA-based wire

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5 CONCLUSION

In the present study, the SMA-based cable has been suggested to use in the cable-stayed cable bridges. To simulate the long-term loading on the characteristics of the SMA wire, as the main component of the SMA-based cable, 1000 cyclic loadings are applied.

The main outcomes of this research are as follows:

1. The energy dissipation of the SMA wires has declined in the first 100 cycles, significantly, then it has reduced smoothly.
2. The residual deformation has reached the maximum effect in the first 100 cycles and after that, it gradually increases.

In order to prevent the remarkable reduction, two suggestions could be considered to better estimate the performance and functionality of SMA-based cable stayed bridges:

1. To cover decreasing the energy absorption ability and increasing the permanent deformation. At least safety factor of 2 is suggested to be considered and design 20% less length of SMA-based elements.
2. Before installation the SMA-based cable, the system should be under 100 cyclic loading with same amplitudes to pass sharp drops in characteristics of the SMA.-based cable.

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