



## Numerical Investigation of Response of the Post-tensioned Tapered Steel Beams with Shape Memory Alloy Tendons

H. Hosseinnajad<sup>a</sup>, M. A. Lotfollahi-Yaghin<sup>1\*</sup><sup>b</sup>, Y. Hosseinzadeh<sup>b</sup>, A. Maleki<sup>a</sup>

<sup>a</sup> Department of Civil Engineering, Maragheh Branch, Islamic Azad University, Maragheh, Iran

<sup>b</sup> Civil Engineering Faculty, University of Tabriz, Tabriz, Iran

### PAPER INFO

#### Paper history:

Received 16 December 2020

Received in revised form 02 March 2021

Accepted 03 March 2021

#### Keywords:

Tapered Steel Beams

Shape Memory Alloy Tendons

External Post-tension

Load Carrying Capacity

Finite Element Analysis

### ABSTRACT

The external post-tension technique is one of the best strengthening methods for reinforcement and improvement of the various steel structures and substructure components such as beams. In the present work, the load carrying capacity of the post-tensioned tapered steel beams with external shape memory alloy (SMA) tendons were studied. 3D nonlinear finite element method with ABAQUS software is used to determine the effects of the increase in the flexural strength, and the improvement of the load carrying capacity. The effect of the different parameters, such as geometrical characteristics and the post-tension force applied to the tendons were also studied in this research. The results revealed that the external post-tension with SMA tendons in comparison with the steel tendons caused a significant improvement of the loading capacity. According to this, using SMA tendon for the reinforcement of the tapered beams resulted in a decrease in weight of these structures and as a consequence responded economic benefits in their application. This method can be used extensively for steel beams due to low executive costs and simplicity of the operation for post-tension.

doi: 10.5829/ije.2021.34.04a.04

## 1. INTRODUCTION

Steel structural may be damaged by overload, high wide load impacts, fire or seismic effect. If this damaged condition is unrepaired, then the condition of the components of this steel structure may be deteriorated. Strengthening implies the addition of structural material in order to achieve adequate stability, member resistance or stiffness. Strengthening and retrofitting the steel structures are common techniques that may be considered if the service loads on the structures are increased or the system exceeds its lifetime. Strengthening and repairing can be applied for both concrete and steel structure as investigated by Islam et al. [1]. Externally post-tensioning technique is one of the most effective ways to retrofit and strengthen the existing structures or overcome the increase in service load without replacement of the other parts of the structure. This method produces the additional stresses in the

direction that opposes to the external loads [2, 3]. Externally post-tensioning beams possess many advantages such as large loading capacity [4], advantageous fracture and fatigue behaviors [5,6], full use of materials and lightweight structural [7], ease in inspection and replacement of tendons, high redundancy and reliability [8].

Issues like weight loss, cost saving, strengthening, and the increase of the load carrying capacity have always occupied researchers minds to invent new methods [9-11]. Therefore, post-tension of the steel sections has been considered seriously. This method has attracted many attentions due to a wide application in building new structures, as well as reinforcement of the old structures. In recent years many research has been devoted to post-tension of metallic structures using materials such as steel rebar [12-14], CFRP bands [15-17] and etc. Chataigner et al. [18] presented the development a new process for fatigue strengthening of

\*Corresponding Author Email: [m.alilotfollahi@gmail.com](mailto:m.alilotfollahi@gmail.com) (M. A. Lotfollahi-Yaghin)

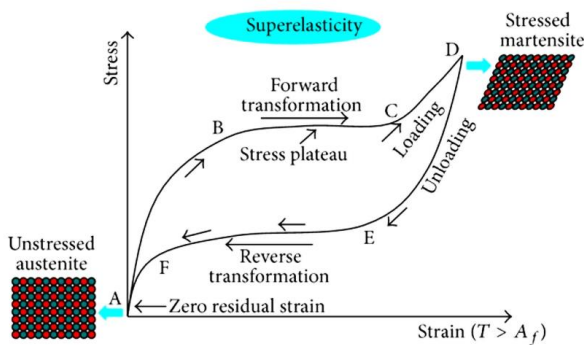
the existing steel bridges with adhesively bonded CFRP laminates. In their study, strain measurement was carried out to verify the theoretical expectations of the reinforcement. Different parameters were studied, including the influence of low traffic volumes during the reinforcement application. The results proved the efficiency of this system for the structure under study. Martinelli et al. [19] investigated the bond behavior of fiber reinforced polymer composites glued to steel substrate; also, the effect of pre-stress, being relevant in practical applications, is also covered in their study. Ultimate unbonded tendon stress in CFRP strengthened post-tensioned indeterminate I-beams cast with HSCS investigated by Maghsoudi and Askari [20]. Comparison of increase in experimental ultimate tendon stress of beams indicates that the increase in tendon stress at ultimate state in strengthened beams is lower than that in non-strengthened beams cast with HSCs.

Ozcatalbas and Ozer [21] studied the mechanical characteristics of the internally post-tensioned I-shaped steel beam by using experimental tests. Saadatmanesh et al. [22] numerically investigated the bending behavior of the composite post-tensioned beams. The results of their study showed that the reinforcement of the metallic structures using the post-tension method increases efficiency and functionality. Reinforced metallic structures demonstrated almost 37% cost saving in comparison with normal structures. Belletti and Gasperi [23] studied the performance of the I-shaped steel beams, which were post-tensioned with tendons. The results of their research revealed that using post-tension method causes a significant decrease in the weight of the beams and hence provides economic benefits and a permanent solution in most of the practical applications. Pisani [24] investigated the behavior of the post-tensioned steel beams using experimental tests. In this research, he studied the amount of the mid-span vertical displacements of the beam for different parameters and loadings. Then he compared the results of the post-tensioned beams with the results of the corresponding sample beams. The results of his research show that using post-tension method causes a 15% decrease in the weight of the structure, which means higher resistance goes with lighter weight. This means that post-tensioned beams have much economic and technical superiority. Ghannam et al. [25] investigated the post-tension of the steel frames and showed that using post-tensioned cables on a bridge with a curved steel beam causes a decrease in the tensions of the main curvy beam and as a consequence increases the loading capacity. Hosseini et al. [17] presented a comparative analysis between the structural performance and cost of using iron-based shape memory alloy (Fe-SMA) vs. carbon fiber reinforced polymer (CFRP) reinforcements for the prestressed strengthening of existing civil structures. The results showed that although the price of Fe-SMA strips is higher than that of the NM

CFRP plates, both of the systems are financially almost equivalent, when the achievable prestressing force and the cost of clamping systems are taken into consideration. Pre-stressed CFRP-strengthening and long-term wireless monitoring of an old roadway metallic bridge investigated by Ghafoori et al. [26].

Park et al. [27] investigated the flexural strength of the external post-tensioned steel beams by using numerical and experimental analysis. They also studied the effect of the post-tension on the improvement of the loading capacity of the I-shaped steel beams under lateral loading. Moradi and Burton [28] compared the theoretical and experimental seismic behavior of the post-tensioned flexural steel frames. El-Zohairy and Salim [29] used the finite element model to study the behavior of the metal cables post-tensioned reinforced steel composite beams. They investigated the effect of the various parameters of the tendons and the tendons separators on the structural characteristics of the composite beams. Taoum et al. [30] applied local post-tension on a steel beam and presented a method in order to reinforce metallic bridges, and I-shaped severely damaged beams. Their results showed that using local post-tension method causes an increase in loading capacity of the I-shaped metallic beam and both post-tension methods (internal or external), ultimate load and yield of the tested beams in comparison with the control beam increase significantly. In some cases, a 25% increase in the loading capacity. The latest research in this field performed Zhou et al. [31]. They studied the external post-tensioned reinforced deep beams with steel tendons. They simulated the beam as Timoshenko beam and, calculated the stress and displacement fields by analytical method. The study of the effective parameters reveals that using post-tension method causes an increase in the loading capacity of these beams in comparison with simple beams and hence, this method is useful and applicable for construction works. A novel un-bonded mechanical clamping system was developed for the strengthening of tensile steel members using pre-stressed carbon fiber reinforced polymer plates by Hosseini et al. [17].

With developing novel engineering materials [32-35], using intelligent materials is one way for making smart structural systems. Shape memory alloys (SMA) are of these materials. SMAs as solid materials have special characteristics in comparison with the other usual materials in engineering [36]. These materials have many benefits such as hardening of the strain, high resistance to corrosion and fatigue, the capability of returning to former shape by applying temperature and, tolerating strain less than 10% without leaving residual strain. Due to their unique characteristics, SMAs could have new functions in many fields such as medical, industrial, aerospace, and engineering applications [37-39]. Figure 1 shows the shape memory performance of these alloys



**Figure 1.** Stress-strain curve and phase conversion in SMAs [53]

and in other words, the stress-strain curve of them in the Martensite phase. The capability of returning to primary shape and, the ability to recover big shape changes are the two special properties of these alloys which civil engineers could use them to construct smart structures. According to this, in recent years numerical and experimental studies have been developing SMAs applications in different civil engineering applications. The SMA materials has been considerably increased due to their peculiar morphing capabilities, which can be relevant for many different engineering applications such as cementitious composites, steel plates, cracked steel bridge connections, self-compacting concrete and shear wall systems [40]. As an example, Tamai and Kitagawa [41] investigated the performance of the SMA cables and their application in earthquake-resistant buildings. Li et al. [42] have presented a new damper based on SMA materials for reinforcing steel structures against seismic loadings. Abou-Elfath [43] presented a novel bracing system for seismic reinforcing of the structures using SMA tendons. There are several investigation that take the advantage of super elasticity characteristic of SMA in improving the mechanical performance of the structural systems [44-46]. Xu et al. [47] experimentally investigated on the self-centering link steel beams using post-tensioned tendons consisting. They used steel rods and shape memory alloy rods to provide re-centering force and energy dissipation capacity of these systems. Xu et al. [48] extended the application of the SMA to self-centering link steel beam and two typical structures for the SMA based self-centering link beams were proposed and analytically modeled. Recently, a comprehensive and more efficient configuration which used steel and SMA rods instead of SMA rods was established for the SMA-based self-centering link-beam by Xu et al. [49]. An experimental study on the pre-treatments of SMA rods and the behaviors of the SMA rods after given pre-treatments were discussed in literature [49]. Performance of steel braced frame reinforced with shape memory alloy wires was investigated by Varughese [50]. Chowdhury et al. [51]

present a new system for improving the seismic performance of post-tensioned self-centering connections using SMA angles or end plates with SMA bolts. Hosseini et al. [52] conduct a comparative analysis between the structural performance and cost of using Fe-SMA vs. CFRP reinforcements for the post-tensioned strengthening of existing civil structures. Izadi et al. [53] propose a series of mechanical anchorage system for strengthening of steel plates with iron-based shape memory (Fe-SMA) strips. In their studies, four different friction-based mechanical clamps to anchor the Fe-SMA strips to the steel substrate were designed and tested.

A comprehensive survey of the literature shows that although a wide variety of studies has been carried out to use SMAs for civil engineering applications so far, there is no investigation for the capability of using these materials in reinforcing steel beams by external post-tension method [54]. Most of the performed investigations in the field of steel beams post-tension have focused on I-shaped steel beams. In the present work, the effect of the external post-tensioned tapered beams with SMA tendons has been investigated. For this purpose, the effect of the various parameters on the loading capacity of these beams has been evaluated using the nonlinear finite element method by ABAQUS software.

## 2. FINITE ELEMENT MODELING

Figure 2 shows the I-shape tapered steel beam used in present work. The I-beam has 4000 mm length, and the distance between two simply supports is 3840 mm. The S235 steel alloy is used, and its mechanical properties are listed in Table 1 [55]. The analysis will be performed on different samples of the I-shaped tapered beams in order to carry out a parametric study. The features of the studied samples along with their appellation are summarized in Table 2.

**TABLE 1.** Mechanical properties of the steel [55]

Steel Grade	$f_y$ [Mpa]	$f_u$ [Mpa]	$\epsilon_u$	$E$ [Gpa]
S235	284±13.8	403±11.0	0.3±0.03	187±16.8

**TABLE 2.** Characteristics of the post-tensioned steel beams studied in this work

Specimens	Prestressed Type	Prestressing force
A (Control specimen)	-	-
B	Steel	1kN
C	SMA	1kN
D	SMA	10kN
E	SMA	20kN

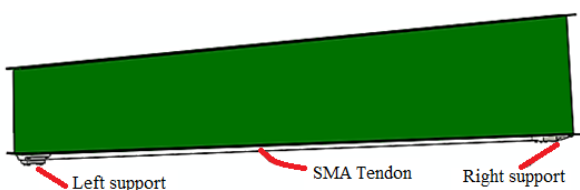
**2. 1. Mechanism of the used Post-tension Technique**

In this work, a new mechanism has been presented to apply the post-tension force, which has high stiffness to minimize loss of recovery stress due to deformations of the clamping and anchoring device. Also, this mechanism have adjustable in order to compensate for imperfections in the length of the bar and the position of the installed clamping device. The geometrical characteristics and dimensions of the anchoring device are shown in Figures 2-4. The novel proposed system is designed to create elongation in SMA tendons and also able to apply the post-tension force in steel beams. The created strain is calculated by measuring the applied displacement to the SMA tendon. With introducing the cross-section of the tendon in calculations, the obtained amount for strain could be used to calculate the amount of the applied force to the beam. Another benefit from this novel presented system is the ability to apply the required force to the SMA tendons without any necessity to the hydraulic jack or other instruments. This system could be easily attached to the tensile flange of the steel beam and, distributes the force to different points of the beam in order to avoid the strain concentration. The anchorage device of SMA Tendons was fixed to the steel beam by the use of M8 bolts. Utilization of the post-tension method presented in this article can alter the position of the plastic hinges. Nonetheless, in some cases, it should be mentioned that due to design errors or defects in these members, the beams tend to lose their strength. Therefore, in these cases, it is vital to reinforce the beam. The given method is presented based on strengthening and improving the beams and can be utilized as reinforcement methods.

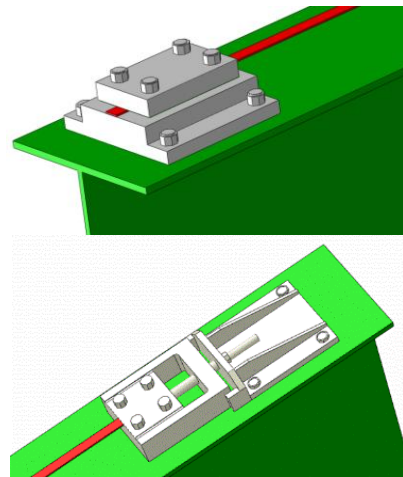
In reinforcing beams using SMA rods, the diameter of these rods as well as the amount of post-tension force are the design parameters and the goal is to control the maximum deflection created in the beam and its buckling load. In addition, it should be noted that SMAs have two super-elasticity and shape memory properties under temperature changes. Accordingly, in this paper, its super-elasticity properties is used to strengthen the beams.

**2. 2. Description of the Mesh and Boundary Conditions**

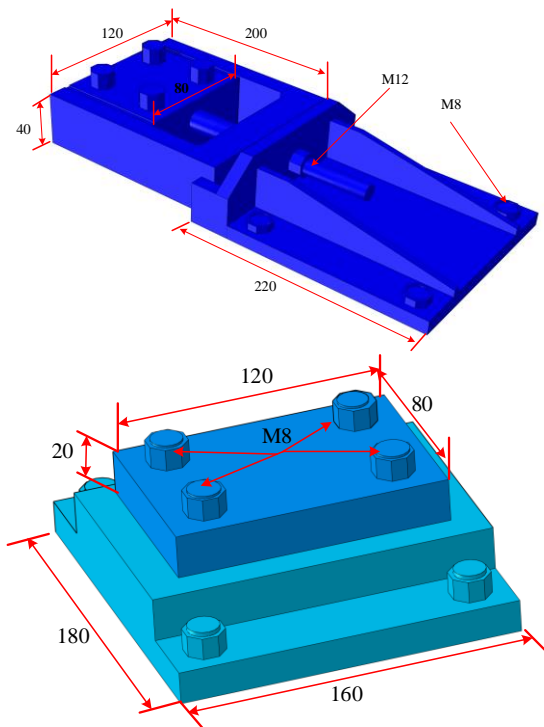
The finite element software of ABAQUS was used to in present work. This software is



**Figure 2.** Mechanism of the post-tension applying system by SMA tendon to the steel beam



**Figure 3.** Supports of the post-tension force applying mechanism



**Figure 4.** Dimensions of the anchoring device

capable of performing different dynamic and static analysis (linear and nonlinear) in 2D and 3D for investigating geometrical and materials nonlinearity. The steel beam was meshed by 3D 8-node (C3D8R) elements, and there were 6 degrees of freedom for the transition on each node. Due to permanent tensional forces applied to SMA tendons, C3D8R elements were used for meshing. The convergence of meshing was performed for choosing the suitable density of mesh and therefore obtaining the acceptable results in faster calculation time. The used

mesh is shown in Figure 5. The bolt load method is utilized to apply the post-tension force. The external load is applied as the displacement of the control to the mid-point of the beam's upper flange. Boundary conditions of the beam have been simulated as two simple supports at both ends and, the degrees of rotation have been limited. The Newton–Raphson incremental iterative solution method was used to solve equations due to performing nonlinear limited element analysis. Individual clamp components such as the upper plate, lower plate, bolts and SMA tendon were independently modeled and assembled in ABAQUS. “Hard” contact was used as the contact property for the normal contact behavior among different elements, whereas the “penalty” friction method was applied for the tangential contact behavior [20].

### 2. 3. Materials Modeling

**2. 3. 1. Steel** Using an appropriate model of materials for simulating materials behavior is crucial for building a suitable model of the steel beams. The results of the study reveal that the nonlinear curve of tension-strain is Roundhouse type. Ramberg–Osgood relationship is usually used to describe the relationship between tension and strain. This relationship is given [56]:

$$\varepsilon = \frac{\sigma}{E_0} + 0.002 \left[ \frac{\sigma}{\sigma_{0.2}} \right]^n \quad (1)$$

where,  $E_0$  is the primary elastic module,  $\sigma_{0.2}$  is the 2% proof stress and,  $n$  is the strain hardening power.  $n$  is obtained from  $\sigma_{0.2}$  and the  $\sigma_{0.01}$  0.01% of the correction tension:

$$n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \quad (2)$$

### 2. 3. 2. Mechanical Simulation of the SMA Behavior

SMA's are special kinds of alloys which can recover their primary shape after being changed by applying external load or tension. The shape memory effect was first discovered by William J. Buehler and coworkers in 1962 while, working on Nickel-titanium at the Naval Ordnance Laboratory [36]. They called this material as Nitinol. Nowadays, Nitinol is the most commonly used SMA in industrial, commercial and, medical applications. Features like having shape memory, superelasticity and, being environment-friendly are significant enough to make this alloy a popular material for the application.

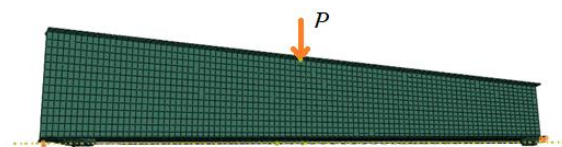


Figure 5. Finite element model of the system

A three-dimensional mechanical constitutive model was used for SMA. The model presents a three-dimensional mechanical constitutive model for SMA. In the follow the mathematical model is briefly described which will be used for the numerical simulations. The model is based on the Gibbs free energy as given below [57]:

$$G(\sigma, T, \xi, \varepsilon) = -\frac{1}{2} \frac{1}{\rho} \sigma : S : \sigma - \frac{1}{\rho} \sigma : \varepsilon + u_0 + f(\xi) \quad (3)$$

where  $\sigma$ ,  $\xi$  and  $\varepsilon$  are defined as the Cauchy stress tensor, martensitic volume fraction, and transformation strain tensor, respectively. Other material constants  $S$ ,  $\rho$ , and  $u_0$  are the effective compliance tensor, density, and effective specific internal energy at reference state and effective entropy at reference state. The hardening function was shown in the equation as  $f(\xi)$ . The constitutive equation in this model relating to the state variable stress ( $\sigma$ ), strain ( $\varepsilon$ ) and temperature ( $T$ ) in the terms of the Martensite volume fraction ( $\xi$ ), is [58]:

$$\sigma - \sigma_0 = E(\xi)(\varepsilon - \varepsilon_0) + \Omega(\xi)(\xi - \xi_0) \quad (4)$$

where  $(\sigma_0, \varepsilon_0, \xi_0)$  represent the initial state or original condition of the material. In this equation,  $E$  is the elastic module and assumed to be a linear function of the Martensite volume fraction as:

$$E(\xi) = E_A + \xi(E_M - E_A) \quad (5)$$

$\Omega$  is called the phase transformation coefficient and is defined as follows:

$$\Omega(\xi) = -\varepsilon_L E(\xi) \quad (6)$$

in which  $\varepsilon_L$  is the maximum recoverable strain. The kinetics equations describing the Martensite volume fraction as an exponential function of stress and temperature are defined as follows:

$$\begin{cases} \xi_{A \rightarrow M} = 1 - \exp(b_M \sigma) \\ \xi_{M \rightarrow A} = 1 - \exp(b_A \sigma) \end{cases} \quad (7)$$

where  $b_A$  and  $b_M$  are material constants.

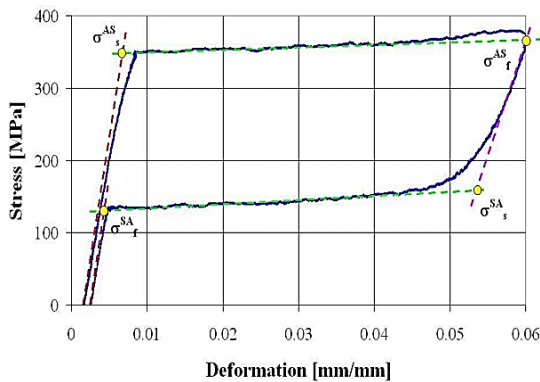
The SMA used in this research is the Nitinol SMA (NiTi) with Nickel-50.8 wt. % and Titanium-49.2 wt. %. Figure 6 shows the stress-deformation curve of the SMA tendon used in this research up to the breaking point. In order to describe the superelastic and memory behavior of the SMA materials, the mechanical characteristics are set according to the behavior model proposed by Zhou et al. [59]. The stress-strain relationship based on this model is implemented into the ABAQUS/Standard code through the user subroutine UMAT. The required parameters for materials in this subroutine are: Young's modulus for both phases of the Austenite and Martensite,

Austenite to Martensite phase beginning tension ( $\sigma_s^{AS}$ ), Austenite to Martensite phase ending tension ( $\sigma_f^{AS}$ ), Martensite to Austenite phase beginning tension ( $\sigma_s^{SA}$ ), Martensite to Austenite phase ending tension ( $\sigma_f^{SA}$ ) and, the length of the super stretching flat strain ( $\epsilon_L$ ). Table 3 contains the behavior characteristics of the NiTi required for its modeling in the software.

### 3. RESULTS AND DISCUSSION

To ensure that numerical finite element models produce the appropriate accuracy, we conducted a convergence study by changing size of elements from comparatively coarse to excessively refined meshes. Figure 7 shows the results obtained for meshes with element sizes ranging from 2 cm to 5 mm for sample of Type-A. The results are shown that 5 mm elements offer an acceptable convergence.

**3. 1. Results Verification** Given that the effect of post-tensioning using SMA tendons on beam behavior has not been studied so far, in order to provide the possibility of comparing the results it is assumed the tendons made of steel. Also, the properties corresponding



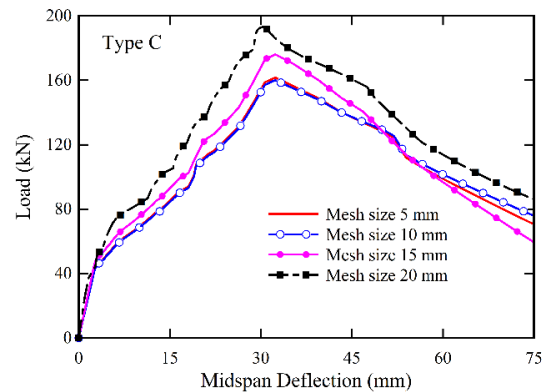
**Figure 6.** Stress-deformation curve of the NiTi SMA tendons used in this study [60]

**TABLE 3** Mechanical characteristics of the NiTi tendons [60]

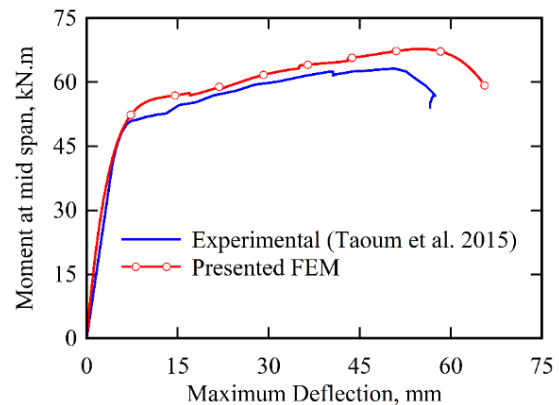
Material parameter	Value
$b_A$ (MPa/°C)	6.73
$b_M$ (MPa/°C)	3.32
$\epsilon_L$ (%)	5.9
$E_A$ (GPa)	67.5
$E_M$ (GPa)	45.4
$\sigma_s$ (MPa)	175
$\sigma_f$ (MPa)	120

to data reported by Taoum et al. [30] are considered in validation analyses. Accordingly, the experimental results of I-shaped steel post-tensioned beams performed by Taoum et al. [30] are used to verify the results from the present work because to this point, no study has been performed in post-tensioning of tapered steel beams. The control beam used in their study will be used in this study as well in order to provide comparability. The comparison of the moment-deflection curve between the experimental results of the mentioned study [30] and the results obtained from the presented finite element model are shown in Figure 8. As can be seen, the finite element modeling predicts the I-shaped steel beams behavior with high precision. According to the comparison, this model can be used to study the effect of the different parameters on the performance of the post-tensioned beams.

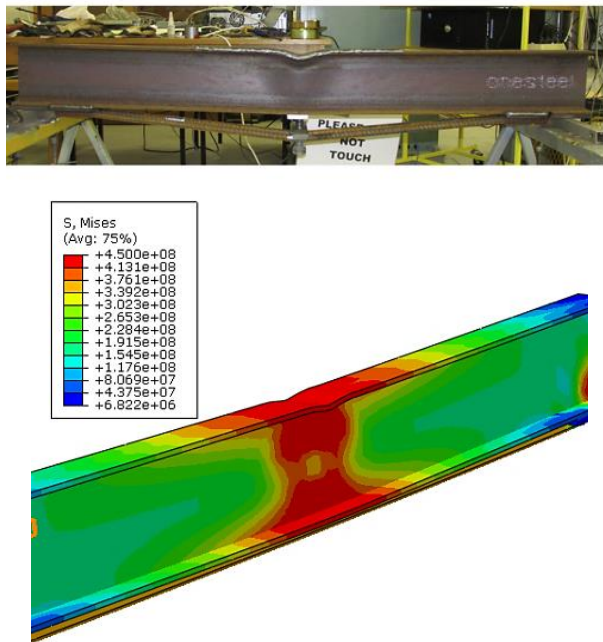
The final deformation of the investigated beam from Taoum et al. [30] and the finite element simulation is shown in Figure 9. Due to the applied force, the mid-point of the beam’s upper flange shows bearing and the local buckling occurs around the force application site.



**Figure 7.** Comparison between different sizes of mesh for Type C



**Figure 8.** Moment-deflection curve obtained from the results of Taoum et al. [30] and, the results by the presented finite element model



**Figure 9.** Final stress distribution (Pa) of the beam obtained from finite element simulation and the experimental results of Taoum et al. [30]

According to the comparison between the occurred deformations of the beam, it can be inferred that the finite element simulation has predicted the post-tensioned beam's deformation with very good precision.

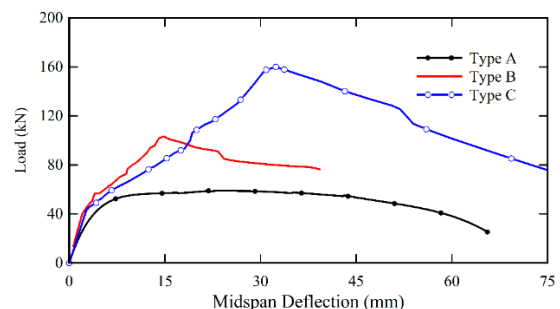
### 3. 2. Investigation of the Effect of the Post-tension with SMA Tendons

After approving the precision of the finite element model by experimental results, in this part, the capability of using SMA tendons for reinforcing the I-shaped tapered steel beams will be investigated. Figure 10 shows the load-deflection curves for samples of A, B and, C. Comparing the post-tensioning of samples B and C with a normal beam sample shows that in general, the post-tensioning causes an increase in the stiffness of the steel beams and therefore decreases the equivalent displacement.

This fact confirms clearly the capability of post-tensioning for steel beams. As an example, the required force for a displacement of 15 mm on the non-reinforced beam equals 56 kN while, for samples B and C (post-tensioned by steel and SMA tendons, respectively) this force equals 113 kN and 95 kN, respectively. For very small displacements (less than 1.4 mm) the performance of the reinforced beam is identical with the non-reinforced sample. This is because that the reinforcing tendons do not operate in such a small distance. Increasing the applied force to the beam activates the reinforcers and they neutralize some of the applied tensions to the tensile flange of the beam. Hence the resistance of the beam against the applied forces

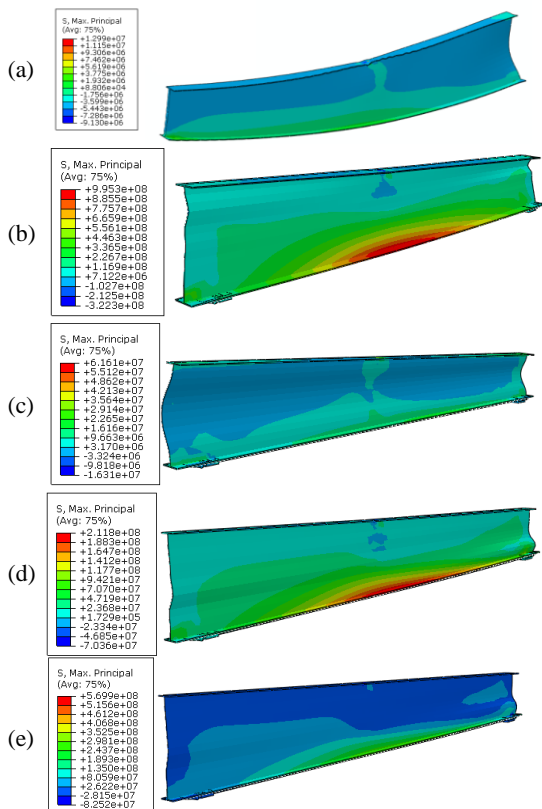
increases. According to Figure 10, the slope of the deflection-load curve for samples B and C is higher for deflections above the 1.3 mm, therefore the equivalent stiffness of the beam increases, as well as its resistance against the forces becomes more. As can be seen, in these regions the effect of the post-tensioning with steel tendons is slightly greater than the sample reinforced with the SMA tendons. The reason for that is the lower strength of the used SMA tendons in comparison with steel tendons at lower strains. As the applied force to the beam increases, it is observed that at the deflection of 17.8 mm the slope of the curve for the sample C increases and hence, the post-tensioning effect becomes better than the sample B. Martensite phase of the SMA tendons turn into Austenite phase at higher strains and, this is the reason for better performance these materials at higher strains. The Young's modulus of the Martensite phase is more than the Austenite phase and thus, at higher strains the occurred phase change causes an increase in the equivalent stiffness of the structure and as a consequence, decreases the deflection of the beam. The nonlinear hardening behavior of the SMA tendons at the strains above the 4% causes an increase in the resistance of them against the deformation and thus, the ultimate force of the beam increases significantly. As an example, the ultimate force for samples B and C equals 102 kN and 168 kN, respectively. According to this fact, the post-tensioning with SMA tendons causes a 40% increase in the ultimate load of the beam in comparison with the steel tendons. These results reveal that post-tensioning of the steel beams using SMA tendons can reduce the dimensions of the structure and hence, decrease the weight of the metallic structure and the costs significantly.

Figure 11 shows the comparison for the deformation of the samples Type-A, Type-B, Type-C, Type-D and, Type-E in order to investigate the effect of the post-tensioning on the created deformation of the tapered steel beams. According to the results, the unreinforced sample shows local buckling along with a sinusoidal half-wave deformation. The application of post-tensioning decreases the amplitude of the deformation and this could be observed for sample Type-B, post-tensioned by the



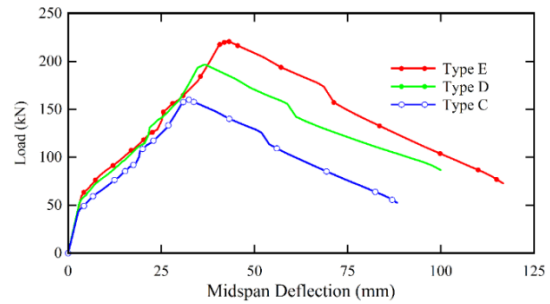
**Figure 10.** Load-deflection curves for samples Type-A, Type-B and Type-C

steel tendons. Figure 11c shows that using SMA tendons at the tensile flange of the beam reinforces this part of the beam and thus, increasing the magnitude of the applied forces causes the buckling in the web of the beam. This type of deformation shows that the SMA tendons have a high capability for resisting against big deformations and this feature causes an increase in the strength of the tensile flange of the beam. Finally, all these effects result in the lessening of the created deformations.



**Figure 11.** Deformations of the tapered steel beams of samples: a) Type-A, b) Type-B and, c) Type-C, d) Type D, e) Type E

Figure 12 shows the load-deflection curves for the samples of Type-C, Type-D and, Type-E. These curves are plotted in order to investigate the effect of the post-tensioning force on the behavior of the steel beams. The results reveal that although the post-tensioning force does not have a significant effect on the yield load of the samples but, as the post-tensioning force increases the effect of this method on the ultimate load of the I-shaped beams increases. As the applied post-tensioning force increases, the ultimate load of the samples Type-D and Type-E are obtained as 195 kN and 225 kN, respectively. Based on this, increasing the post-tensioning force from 1 kN to 10 kN and 20 kN increases the ultimate load of



**Figure 12.** Load-deflection curves for samples Type-C, Type-D, and Type-E

the beams 17.5% and 26.7%, respectively. As can be seen, increasing the post-tensioning forces reveal the effect of the post-tensioning method on the increment of the ultimate load. As an example, for the applied force of 100 kN, although the sample beam loses the loading capacity, the maximum mid-span deflection of sample Type-C is 18.8 mm while, this value for samples Type-D and Type-E are 15.6 mm and 15.3 mm, respectively. Hence, increasing the post-tensioning force causes an increase in the equivalent stiffness of the structure and therefore, decrease the deformations of the steel beams.

Table 4 shows a summary of the results related to the displacement and yield load of the investigated samples. Ultimate displacements, ultimate loads, and maximum lateral displacement of the samples are also included in Table 4. According to the results, it is obvious that using external post-tensioning method causes a significant increase in the yield load and the ultimate load of the tapered steel beams than the control beam. The amount of the applied force to the SMA tendons has a direct effect on these results. Increasing the amount of the post-tensioning force increases the pressure strains applied to the tensile flange of the beam, and hence improves the loading capacity of the beams.

SMA's have multiple industrial and medical applications, and the prices of materials used in the medical industry have been trending upwards. However,

**TABLE 4.** A summary of the results related to the displacement, the ultimate and the yield load of the investigated samples

Beam Type	Pre-stressing Force	Yield Load (kN)	Yield Disp. (mm)	Ultimate Load (kN)	Ultimate Disp. (mm)	Max. Lateral Disp. (mm)
A	-	34.4	3.6	-	-	8
B	1kN	39.1	2.1	102.6	14.5	3
C	1kN	41.3	2.6	160	32.3	2.8
D	10kN	55.2	3.2	196	35.9	2.5
E	20kN	63.4	4.1	221	42.6	1.7



recently, thanks to the considerable increase in these materials' production by various companies, the cost of materials used in its industrial applications has decreased significantly. According to the data available, some of these rods' prices is about 3 \$/kilogram. Nevertheless, it should be noted that for the beam under study, which has 4 meters length, roughly 1.1 kg of SMA rod is used. In any case, the spectacular improvement in the use of these materials in increasing the bearing capacity of this beam (40% improvement of SMA compared to steel rebars), their use is both economically and practically justifiable.

#### 4. CONCLUSIONS

The investigation of the performed studies in the field of the tapered metallic beams improvement reveals that although these structures are practical, few studies have been performed about reinforcing and improving them. So far, no study has been carried out to investigate the applicability of local post-tension method using SMA tendons. In the present work, a novel design is presented for creating post-tension in beams and also, the finite element method is used to evaluate the applicability of the SMA tendons for reinforcing the I-shaped tapered steel beams by external post-tension method. The results reveal that using SMA tendons causes a significant increase in the loading capacity of these beams. Furthermore, in identical condition using these materials for post-tensioning causes a 40% increase in the ultimate load of the beam in comparison with the steel tendons. On the other hand, increasing post-tension force from 1 kN to 10 kN and 20 kN, increases the ultimate load of the beams 17.5% and 26.7%, respectively. Reinforcing the web of the beam helps to increase the loading capacity of the beam. It can be concluded that the external post-tension of the I-shaped tapered steel beams using SMA tendons is a very practical method for reinforcing and improving these beams. This method increases the equivalent stiffness of the beam and hence prevents sudden destruction and also decreases the implementation costs of the metallic structures. The amount of the post-tension force and the geometrical characteristics of the beams are effective on the reinforcement of the steel beams.

#### 5. REFERENCES

- Islam, M., Rubieyat B.A., and Moushtakim B., "Strengthening Techniques of Steel Structure: An Overview", *World Scientific News*, Vol. 118, (2019), 181-193.
- Farhadi, N., Saffari, H., Torkzadeh, P., "Evaluation of Seismic Behavior of Steel Moment Resisting Frames Considering Nonlinear Soil-structure Interaction", *International Journal of Engineering, Transactions A: Basics*, Vol. 31, No. 7, (2018), page no. 1020-1027. DOI: 10.5829/ije.2018.32.07a.03
- Barkhordari, M.S., Tehranizadeh, M., "Ranking Passive Seismic Control Systems by Their Effectiveness in Reducing Responses of High-Rise Buildings with Concrete Shear Walls Using Multiple-Criteria Decision Making", *International Journal of Engineering, Transactions B: Applications*, Vol. 33, No. 8, (2020), 1479-1490. DOI: 10.5829/ije.2020.33.08b.06
- Yangzhi, R., Wang, Y., Wang, B., Ban, H., Song, J., Su, G., "Flexural behavior of steel deep beams prestressed with externally unbonded straight multi-tendons", *Thin-Walled Structures*, Vol. 131, (2018), 519-530. DOI: 10.1016/j.tws.2018.07.022
- Maleki, F.K., and Toygar, M.E., "The fracture behavior of sandwich composites with different core densities and thickness subjected to mode I loading at different temperatures", *Materials Research Express*, Vol. 6, No. 4, (2019), 045314. DOI: 10.1088/2053-1591/aafc02
- Huawen, Y., Cuijuan, L., Shiling, P., Tomas, U., Haobo, Q., "Fatigue performance analysis of damaged steel beams strengthened with prestressed unbonded CFRP plates", *Journal of Bridge Engineering*, Vol. 23, No. 7, (2018), 04018040. DOI: 10.1061/(ASCE)BE.1943-5592.0001251
- Kambal, M., and Jia, Y., "Theoretical and experimental study on flexural behavior of prestressed steel plate girders", *Journal of Constructional Steel Research*, Vol. 142, (2018), 5-16. DOI: 10.1016/j.jcsr.2017.12.007
- Ayyub, B.M., Sohn, Y.G., and Saadatmanesh, H., "Prestressed composite girders under positive moment", *Journal of Structural Engineering*, Vol. 116, No. 11, (1990), 2931-2951. DOI: 10.1061/(ASCE)0733-9445(1990)116:11(2931)
- Imran, M., Mahendran, M., and Keerthan, P., "Experimental and numerical investigations of CFRP strengthened short SHS steel columns", *Engineering Structures*, Vol. 175, (2018), 879-894. DOI: 10.1016/j.engstruct.2018.08.042
- Izadi, M.R., Ghafoori, E., Shahverdi M., Motavalli, M., Maalek, S., "Development of an iron-based shape memory alloy (Fe-SMA) strengthening system for steel plates", *Engineering Structures*, Vol. 174, (2018), 433-446. DOI: 10.1016/j.engstruct.2018.07.073
- Kazem, H., Zhang, Y., Rizkalla, S., Seracino, R., Kobayashi, A., "CFRP shear strengthening system for steel bridge girders", *Engineering Structures*, Vol. 175, (2018), 415-424. DOI: 10.1016/j.engstruct.2018.08.038
- Haskett, M., Oehlers, D.J., and Mohamed Ali, M.S., "Local and global bond characteristics of steel reinforcing bars", *Engineering Structures*, Vol. 30, No. 2, (2008), 376-383. DOI: 10.1016/j.engstruct.2007.04.007
- Franco, N., Biscaia, H., and Chastre, C., "Experimental and numerical analyses of flexurally-strengthened concrete T-beams with stainless steel", *Engineering Structures*, Vol. 172, (2018), 981-996. DOI: 10.1016/j.engstruct.2018.06.077
- Özbek, E., Aykaç, B., and Aykaç, S., "The effects of brick walls strengthened with perforated steel plates on frame behavior", *Engineering Structures*, Vol. 189, (2019), 62-76. DOI: 10.1016/j.engstruct.2019.03.080
- Chataigner, S., Benzarti, K., Foret, G., Caron, J.F., Gemighani, G., Brugiolo, M., Calderon, I., Pinero, I., Birtel, V., Lehmann, F., "Design and testing of an adhesively bonded CFRP strengthening system for steel structures", *Engineering Structures*, Vol. 177, (2018), 556-565. DOI: 10.1016/j.engstruct.2018.10.004
- Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A., Zhao, X.L., Al-Mahaidi, R., Terraso, G., "Development of prestressed unbonded and bonded CFRP strengthening solutions for tensile metallic members", *Engineering Structures*, Vol. 181, (2019), 550-561. DOI: 10.1016/j.engstruct.2018.12.020
- Hosseini, A., Michels, J., Izadi, M., Ghafoori, E., "A comparative study between Fe-SMA and CFRP reinforcements for prestressed strengthening of metallic structures", *Construction and Building*

- Materials*, Vol. 226, (2019), 976-992. DOI: 10.1016/j.conbuildmat.2019.07.169
18. Chataigner, S., Wahbeh, M., Garcia-Sanchez, D., Benzarti, K., "Fatigue Strengthening of Steel Bridges with Adhesively Bonded CFRP Laminates: Case Study", *Journal of Composites for Construction*, Vol. 24, No. 3, (2020), 05020002. DOI: 10.1061/(ASCE)CC.1943-5614.0001014
  19. Martinelli, E., Hosseini, A., Ghafoori, E., Motavalli, M., "Behavior of prestressed CFRP plates bonded to steel substrate: Numerical modeling and experimental validation", *Composite Structures*, Vol. 207, (2019), 974-984. DOI: 10.1016/j.compstruct.2018.09.023
  20. Maghsoudi, A., Askari Y., "Ultimate Unbonded Tendon Stress in CFRP Strengthened Post-Tensioned Indeterminate I-Beams Cast with HSCs", *International Journal of Engineering, Transactions C: Aspects*, Vol. 28, No. 3, (2015), 350-359. DOI: 10.5829/idosi.ije.2015.28.03c.03
  21. Ozcatalbas, Y., and Ozer, A., "Investigation of fabrication and mechanical properties of internally prestressed steel I beam", *Materials & Design*, Vol. 28, No. 6, (2007), 1988-1993. DOI: 10.1016/j.matdes.2006.04.007
  22. Saadatmanesh, H., Albrecht, P. and Ayyub, B.M., "Experimental study of prestressed composite beams", *Journal of Structural Engineering*, Vol. 115, No. 9, (1989), 2348-2363. DOI: 10.1061/(ASCE)0733-9445(1989)115:9(2348)
  23. Belletti, B., and Gasperi, G., "Behavior of prestressed steel beams", *Journal of Structural Engineering*, Vol. 136.9, (2010), page no. 1131-1139. DOI: 10.1061/(ASCE)ST.1943-541X.0000208
  24. Pisani, M.A., "A numerical survey on the behaviour of beams prestressed with FRP cables", *Construction and Building Materials*, Vol. 12, No. 4, (1998), 221-232. DOI: 10.1016/S0950-0618(97)00081-0
  25. Ghannam, M., Mahmoud, N.S., Badr, A., Salem, F.A., "Effect of post tensioning on strengthening different types of steel frames", *Journal of King Saud University-Engineering Sciences*, Vol. 29.4, (2017), 329-338. DOI: 10.1016/j.jksues.2016.07.001
  26. Ghafoori, E., Hosseini, A. Al-Mahaidi, R., Zhao, X.L., Motavalli, M., "Prestressed CFRP-strengthening and long-term wireless monitoring of an old roadway metallic bridge", *Engineering Structures*, Vol. 176, (2018), 585-605. DOI: 10.1016/j.engstruct.2018.09.042
  27. Park, S., Kim, T., Kim, K., Hong, S.N., "Flexural behavior of steel I-beam prestressed with externally unbonded tendons", *Journal of Constructional Steel Research*, Vol. 66.1, (2010), 125-132. DOI: 10.1016/j.jcsr.2009.07.013
  28. Moradi, S., and Burton, H.V., "Response surface analysis and optimization of controlled rocking steel braced frames", *Bulletin of Earthquake Engineering*, Vol. 16, No. 10, (2018), 4861-4892. DOI: 10.1007/s10518-018-0373-1
  29. El-Zohairy, A., and Salim, H., "Parametric study for post-tensioned composite beams with external tendons", *Advances in Structural Engineering*, Vol. 20, No. 10, (2017), 1433-1450. DOI: 10.1177/1369433216684352
  30. Taoum, A., Jiao, H., and Holloway, D., "Upgrading steel I-beams using local post-tensioning", *Journal of Constructional Steel Research*, Vol. 113, (2015), 127-134. DOI: 10.1016/j.jcsr.2015.06.012
  31. Zhou, H., Hao, C., Zheng, Z., Wang, W., "Numerical Studies on Fire Resistance of Prestressed Continuous Steel-Concrete Composite Beams", *Fire Technology*, (2019), 1-19. DOI: 10.1007/s10694-019-00916-7
  32. Gruyter, D., "Stability analysis of FGM microgripper subjected to nonlinear electrostatic and temperature variation loadings", *Science and Engineering of Composite Materials*, Vol. 23, No. 2, (2016), 199-207. DOI: 10.1515/secm-2014-0079
  33. Maleki, V.A., and Mohammadi, N., "Buckling analysis of cracked functionally graded material column with piezoelectric patches", *Smart Materials and Structures*, Vol. 26, No. 3, (2017), 035031. DOI: 10.1088/1361-665X/aa5324
  34. Toygar, M.E., Tee, K.F., Maleki, F.K., Balaban, A.C., "Experimental, analytical and numerical study of mechanical properties and fracture energy for composite sandwich beams", *Journal of Sandwich Structures & Materials*, Vol. 21, No. 3, (2019), 1167-1189. DOI: 10.1177/1099636217710003
  35. Chong, K.P., and Garboczi, E.J., "Smart and designer structural material systems", *Progress in Structural Engineering and Materials*, Vol. 4, No. 4, (2002), 417-430. DOI: 10.1002/pse.134
  36. Song, G., Ma, N., and Li, H.N., "Applications of shape memory alloys in civil structures", *Engineering Structures*, Vol. 28, No. 9, (2006), 1266-1274. DOI: 10.1016/j.engstruct.2005.12.010
  37. Wang, W., Fang, C., Yang, X., Chen, Y., Ricles, J., Sause R., "Innovative use of a shape memory alloy ring spring system for self-centering connections", *Engineering Structures*, Vol. 153, (2017), 503-515. DOI: 10.1016/j.engstruct.2017.10.039
  38. Abouali, S., Shahverdi, M., Ghassemieh, M., Motavalli, M., "Nonlinear simulation of reinforced concrete beams retrofitted by near-surface mounted iron-based shape memory alloys", *Engineering Structures*, Vol. 187, (2019), 133-148. DOI: 10.1016/j.engstruct.2019.02.060
  39. Elbahi, Y.I., and Youssef, M.A., "Flexural behaviour of superelastic shape memory alloy reinforced concrete beams during loading and unloading stages", *Engineering Structures*, Vol. 181, (2019), 246-259. DOI: 10.1016/j.engstruct.2018.12.001
  40. Dehghani, A., and Aslani, F., "The effect of shape memory alloy, steel, and carbon fibres on fresh, mechanical, and electrical properties of cementitious composites", *Cement and Concrete Composites*, Vol. 112, (2020), 103659. DOI: 10.1016/j.cemconcomp.2020.103659
  41. Tamai, H., and Kitagawa, Y., "Pseudoelastic behavior of shape memory alloy wire and its application to seismic resistance member for building", *Computational Materials Science*, Vol. 25, No. 1-2, (2002), 218-227. DOI: 10.1016/S0927-0256(02)00266-5
  42. Li, H.N., Liu, M.M., and Fu, X., "An innovative re-centering SMA-lead damper and its application to steel frame structures", *Smart Materials and Structures*, Vol. 27, No. 7, (2018), 075029. DOI: 10.1088/1361-665X/aac28f
  43. Abou-Elfath, H., "Evaluating the ductility characteristics of self-centering buckling-restrained shape memory alloy braces", *Smart Materials and Structures*, Vol. 26.5, (2017), 055020. DOI: 10.1088/1361-665X/aa6abc
  44. Fang, C., Zheng, Y., Chen, J., Yam, M.C.H., Wang, W., "Superelastic NiTi SMA cables: Thermal-mechanical behavior, hysteretic modelling and seismic application", *Engineering Structures*, Vol. 183, (2019), 533-549. DOI: 10.1016/j.engstruct.2019.01.049
  45. Wang, B., Jiang, H., and Wang, J., "Numerical simulation and behavior insights of steel columns with SMA bolts towards earthquake resilience", *Journal of Constructional Steel Research*, Vol. 161, (2019), 285-295. DOI: 10.1016/j.jcsr.2019.07.011
  46. Varughese, K., and El-Hacha, R., "Design and behaviour of steel braced frame reinforced with NiTi SMA wires", *Engineering Structures*, Vol. 212, (2020), 110502. DOI: 10.1016/j.engstruct.2020.110502
  47. Xu, X., Tu, J., Cheng, G., Zheng, J., Luo, Y., "Experimental study on self-centering link beams using post-tensioned steel-SMA

- composite tendons", *Journal of Constructional Steel Research*, Vol. 155, (2019), 121-128. DOI: 10.1016/j.jcsr.2018.12.026
48. Xu, X., Zhang, Y., and Luo, Y., "Self-centering modularized link beams with post-tensioned shape memory alloy rods", *Engineering Structures*, Vol. 112, (2016), 47-59. DOI: 10.1016/j.engstruct.2016.01.006
49. Xu, X., Zheng, Y., and Luo, Y., "Self-centering links using post-tensioned composite tendons", *Advances in Structural Engineering*, Vol. 21.9, (2018), 1302-1312. DOI: 10.1177/1369433217742523
50. Varughese, K.A., "Performance of Steel Braced Frame Reinforced with Shape Memory Alloy Wires". MS thesis. Schulich School of Engineering, 2019.
51. Chowdhury, M.A., Rahmzadeh, A., and Shahria Alam, M., "Improving the seismic performance of post-tensioned self-centering connections using SMA angles or end plates with SMA bolts", *Smart Materials and Structures*, Vol. 28.7, (2019), 075044. DOI: 10.1088/1361-665X/ab1ce6
52. Hosseini, A., Ghafoori, E., Al-Mahaidi, R., Zhao, X.L., Motavalli, M., "Strengthening of a 19th-century roadway metallic bridge using nonprestressed bonded and prestressed unbonded CFRP plates", *Construction and Building Materials*, Vol. 209, (2019), 240-259. DOI: 10.1016/j.conbuildmat.2019.03.095
53. Izadi, M., Ghafoori, E., Hosseini, A., Motavalli, M., "Development of anchorage systems for strengthening of steel plates with iron-based shape memory alloy strips", Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017). No. CONF. 2017.
54. Aizawa, S., Kakizawa, T., and Higashino, M., "Case studies of smart materials for civil structures", *Smart Materials and Structures*, Vol. 7, No. 5, (1998), 617. DOI: 10.1088/0964-1726/7/5/006
55. Duarte, A.P.C., Silva, B.A., Silvestre, N., Brito, J., Julio, E., Castro, J.M., "Tests and design of short steel tubes filled with rubberised concrete", *Engineering Structures*, Vol. 112, (2016), page no. 274-286. DOI: 10.1016/j.engstruct.2016.01.018
56. Tao, Z., Uy, B., Liao, F.Y., Han, L.H., "Nonlinear analysis of concrete-filled square stainless steel stub columns under axial compression", *Journal of Constructional Steel Research*, Vol. 67.11, (2011), 1719-1732. DOI: 10.1016/j.jcsr.2011.04.012
57. Eshghinejad, Ahmadreza. Finite element study of a shape memory alloy bone implant. Ph.D. Diss. University of Toledo, 2012.
58. Sayyaadi, H., Zakerzadeh, M.R., and Salehi, H., "A comparative analysis of some one-dimensional shape memory alloy constitutive models based on experimental tests", *Scientia Iranica*, Vol. 19.2, (2012), 249-257. DOI: 10.1016/j.scient.2012.01.005
59. Zhou, B., Yoon, S.H., and Leng, J.S., "A three-dimensional constitutive model for shape memory alloy", *Smart Materials and Structures*, Vol. 18.9, (2009), 095016. DOI: 10.1088/0964-1726/18/9/095016
60. Fugazza, D., "Experimental investigation on the cyclic properties of superelastic NiTi shape-memory alloy wires and bars", Individual study, European School for Advanced Studies in Reduction of Seismic Risk ROSE School, Pavia, Italy (2005).

---

### Persian Abstract

---

#### چکیده

روش پس‌تنیدگی خارجی یکی از بهترین روش‌ها به منظور تقویت و بهسازی تیرها می‌باشد. در تحقیق حاضر، ظرفیت باربری تیرهای فولادی با مقطع متغیر پس‌تنیده شده با تاندون خارجی از جنس آلیاژهای حافظه‌دار شکلی (Shape Memory Alloy) یا به اختصار SMA مورد مطالعه قرار داده می‌شود. بدین منظور، ضمن ارائه مکانیزم جدیدی جهت اعمال پس‌تنیدگی به تیرهای فولادی، کارایی این روش در نمونه‌های متنوعی از تیرهای فولادی I شکل با مقطع متغیر مطالعه می‌شود. جهت تعیین میزان افزایش مقاومت خمشی و بهبود ظرفیت باربری و همچنین تأثیر پارامترهای مختلف مانند مشخصات هندسی تیر و نیروی پس‌تنیدگی اعمالی به تاندون‌ها، از روش المان محدود غیرخطی و نرم‌افزار اجزای محدود آباکوس استفاده می‌شود. نتایج نشان می‌دهد که پس‌تنیدگی خارجی با استفاده از تاندون‌های SMA، باعث بهبود قابل ملاحظه‌ای در ظرفیت باربری آنها نسبت به پس‌تنیدگی با میلگردهای فولادی می‌شود. بر این اساس، استفاده از تاندون SMA به منظور تقویت تیرهای مقطع متغیر می‌تواند باعث کاهش وزن این سازه‌ها و در نتیجه اقتصادی‌تر شدن کاربرد آنها باشد. علاوه بر این، این روش به دلیل هزینه‌های اجرایی پایین و سهولت عملیات برای ایجاد پس‌تنیدگی می‌تواند به صورت گسترده در تیرهای فولادی مورد استفاده قرار گیرد.

---