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Theoretical Analysis on the Behavior of Reinforced Industrial Shed Structures with Shape Memory Alloys

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ABSTRACT

Shape memory alloys (SMAs) are functional materials that feature shape memory effects and super-elasticity. These features have made SMAs efficient materials for reinforcement and improvement of the stability of a structure. The present study investigated the effect of local post-tensioning with SMAs to improve the load-carrying capacity of tapered steel industrial sheds. For this purpose, ABAQUS software was used to predict the flexural strength and load-bearing capacity of the alloys. The effects of the diameter and the post-tension force applied to the SMA tendons were investigated. The results showed that external post-tensioning using SMA tendons is an effective way to increase the load-carrying capacity of industrial sheds. In the maximum load capacity of the frame for the steel and SMA tendons increased by 36 and 60%, respectively. The performance of the sheds was improved by local post-tensioning, which can reduce the weight of the structures.

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1. INTRODUCTION

Industrial metal structures have been used for a wide nge of applications in different factories; such as poultry houses and aircraft hangars to sport stadiums. This means that it is necessary to improve and reinforce existing industrial metal structures to enhance their performance and stability. In the past, post-tensioning technology has been extensively used to reinforce concrete and metal structures; however, the effects of post-tensioning on industrial sheds have not yet been investigated. The improvement of the load-carrying capacity of tapered steel industrial sheds using post-tensioning technology also has not been investigated.

The high cost of installing new sheds has made it necessary to develop ways of reinforcing steel industrial sheds. The post-tensioning method is an available approach to strengthening an existing structure to cope with an increase in service loading. In this technology, some parts of the structure are reinforced in order to increase the total load-carrying capacity of the structure.

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In the past two decades, post-tensioning has been commonly used to improve the performance of steel and concrete structures [1-12]. Nunziata [13] investigated the behavior of post-tensioned steel beams through experimental analysis. The results indicated that post-tensioning resulted in a 15% decrease in the weight of the structure.

Post-tensioned beams have technical and financial advantages over more simply fabricated structures. Studies have examined the use of post-tensioning cables in earthquake-resistant structural steel moment-resisting frames [14-17]. Nazir [18] applied post-tensioned cables to a bridge with a curved steel beam. Their results indicated that post-tensioning increased the load-carrying capacity of the structure as a suitable and affordable approach to the reinforcement of existing steel structures.

In the post-tensioning technique, prestress is introduced with the use of tensioning tendons because, when tendons are grouted, re-tensioning is impossible. Researchers have explored prestressing techniques that employ SMAs to overcome this disadvantage of conventional prestressing. SMAs possess physical and mechanical features that make them successful

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candidates for use in structural engineering applications. They can regain their original shape after being deformed up to 6 to 8% as a result of underlying reversible solid-solid phase transformation. SMAs have shown promise, especially for applications in which the added value is more important than purely economic considerations. Some of the advantages of SMAs include bio-compatibility, usefulness for a variety of applications, and good mechanical properties, such as strength and corrosion resistance [21].

Park et al. [19] performed a numerical study using ABAQUS software to investigate the effect of post-tensioning method to increase the flexural strength and load-carrying capacity of I-shaped steel beams. The results indicated that the external prestressing technique creates a stiffer steel beam by applying suitable prestresses when parameters are appropriately combined. Taoum et al. [20] applied local post-tensioning to a steel beam for reinforcement of damaged steel bridges and I-shaped beams. The results showed that post-tensioning technology could be extensively used for steel beams due to its low cost and ease of preparation. Ghannam et al. [15] studied the effect of post-tensioned cables for strengthening steel frames (simple, double-bay, and double-story frames) using ANSYS finite element (FE) method. The results of the FE models indicated that the use of post-tensioned cables significantly increased the load capacity of the steel frame. The post-tensioning force must be designed to ensure that the connections remain safe after post-tensioning. In other words, the structural connections must also be considered for the design of post-tensioning forces.

The development of materials research has led to intelligent materials such as metals (e.g. shape-memory nickel-titanium alloy), ceramics, and SMAs, which can alter their properties to adapt to changes in the environment. Several studies have focused on the application of SMAs to structures [21–24]. A review of the use of SMAs in civil engineering applications can be found by Chang and Araki [25]. Shrestha et al. [26] evaluated the behavior of concrete structures optimally equipped with SMAs as they are being used along with plastic hinge of the beams. For this purpose, a reinforced concrete (RC) beam, a 2D RC frame, and a 3D RC building were considered, which were tested in previous studies under cyclic loading and on a shaking table. Daghash and Ozbulut [27] studied the cyclic behavior of composite materials reinforced with super-elastic NiTi SMA wires using uniaxial tensile tests. The results of the tests indicated that the SMA-FRP composites can recover from relatively high strains upon unloading and also revealed very high damage strains. Strieder et al. [28] performed an experimental study on the behavior of concrete beams post-tensioned with steel-based SMAs. They found that the serviceability behavior of a concrete beam improved by the application of a second thermal activation at different temperatures and stress states for activation along the SMA strip. The study on application of shape memory alloys in had been done previously with different methods. This new material have the unique ability to sustain large deformations and returned to their original shape upon stress applied for superelastic SMA or by heating the SMA. Shape memory alloys due to their benefits of superelasticity and shape-memory effect have been successfully used in a number of industries and civil engineering such as pre-stressing, pre-tensioning, post-tensioning, SMA based dampers, etc. The benefits of using SMAs in pre-stressing are:

- Active control on the amount of pre-stressing with increased additional load-carrying capacity.
- No involvement of jacking or strand-cutting.
- No elastic shortening friction and anchorage losses over time.

Conventional pre-stressing of concrete members by pre-tensioning wires requires jacking and release of pre-stressing strands, which causes crack at the end of the girders during strand cutting. So, if we use SMA for pre-stressing, than jacking or strand-cutting are not required. A literature review showed that many studies have been done in the field of strengthening concrete structures using SMA, which shows the significant effect of SMA in increasing the bearing capacity of these members. However, this method has not been used in the case of steel structures, which was the main purpose of the present study. The main advantages are that the SMA bars do not need ducts nor anchorages and have no friction during pre-stressing or post-stressing.

A review of previous studies has shown that the application of post-tensioning to steel structures became a common way to reduce the cost and weight of structures. The use of high-strength steel tendons and post-tensioning can allow a decrease in the size of the steel elements and increase the load-carrying capacity of the structures. In recent years, the application of the post-tensioning method to steel structures has been investigated; but the application of this method to improve the characteristics of industrial sheds has not been considered. The present study investigated the use of this method as well as the application of SMA tendons as reinforcing structures using FE simulations using ABAQUS software. The effects of the diameter and the post-tension force applied to the SMA tendons were investigated. The results showed that external post-tensioning using SMA tendons is an effective way to increase the load-carrying capacity of industrial sheds. For the maximum load capacity of the frame, the steel and SMA tendons had an increase of 36 and 60%, respectively. The performance of the sheds was improved by local post-tensioning, which can reduce the weight of the structures.

2. NUMERICAL SIMULATION

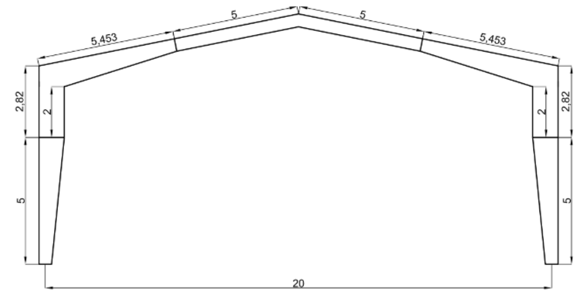
2. 1. 3D Model Details As shown in Figure 1, an industrial shed of 20 m in length with a height that varies from 7 m at the supports to 9 m at the midspan was investigated. The slope of the roof in all models is 20%. The type of steel used is ST275. The cross-section of the rafter and column is I-shaped and has a variable cross-section. In all the studied models, the lateral bearing system in the transverse direction is considered as a normal bending frame and in the longitudinal direction, a simple frame with a conventional converging brace is assumed. For analysis and design of the industrial shed structure, ETABS2018 software was used depending on American code AISC 360-10 and the steel profile will be analyzed by using both LRFD design provisions according to AISC 360-10 and ASCE 7-16. Beams and columns are considered as beam elements to carry their weight, additional dead load, and the live load as gravity distributed pressures. The design loading combinations are the number of combinations of the prescribed response cases for which the building is to be checked/designed. In the LFRD method design shall be performed according to AISC Committee [29]:

$$R_u \leq \phi R_n \tag{1}$$

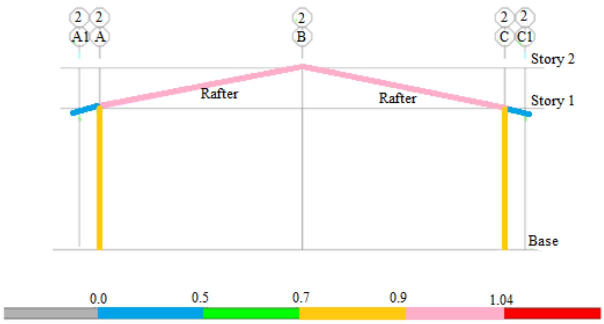
where R_u is required strength using LRFD load combinations, R_n is nominal strength, and ϕ is the resistance factor. The performance characteristics of the designed sections obtained based on the LFRD method in ETABS software is shown in Figure 1. As can be seen, the designed frame has a good performance.

2. 2. Modeling in ABAQUS In the current study, the effect of local post-tensioning technology on the performance of steel industrial sheds has been investigated. For this purpose, an industrial steel shed was designed in ETABS software based on the LFRD method and this structure then was simulated in ABAQUS. The results were used to apply monotonic loading to study the effects of diameter of the elements, type of material and post-tensioning force on the performance of structure.

The structure was of grade S275 steel with an elastic modulus of 187 MPa, the yield stress of 275 MPa, the ultimate strength of 430 MPa and failure strain of 0.33. The structure was meshed using 3D C3D8R elements. The convergence of meshing was checked for the selection of a suitable mesh density to improve analysis precision and reduce computing time. Based on the



(a)



(b)

Figure 1. (a) Geometric characteristics of the tapered steel industrial shed used in finite element analysis, (b) The performance characteristics of the designed sections

initial results of the analysis, 0.02 cm was chosen as the size of the elements. The bolt load method was used for applying the post-tension load. Analysis was performed under displacement control. The boundary conditions were simulated as joint supports below the columns. Figure 2 shows the employed details of the FE model. The Newton–Raphson incremental iterative solution method was used to solve the equations in nonlinear FE analysis.

2. 3. Mechanical Features of SMA Tendons As stated, the novelty of this study was the reinforcement of steel industrial sheds using SMA tendons under

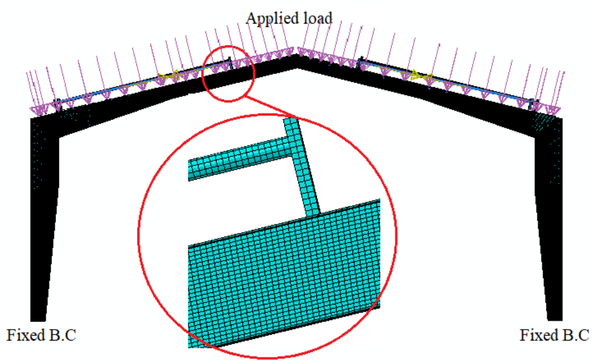


Figure 2. Employed details of the FE model

external post-tensioning. The reversible phase change of SMAs in intelligent materials composed of gold-cadmium (Au-Cd) was first observed by Chang and Read [30]. Nili Ahmadabadi et al. [31] reorted the shape memory properties in nickel-titanium (Ni-Ti) alloy. At present, several types of SMA have been developed and used by different researchers.

Ni-Ti alloy, known as Nitinol, has many applications in practical engineering because of its high thermomechanical and thermoelectric characteristics. SMAs have two main phases, austenite and martensite, that are stable at low and high strain levels, respectively [34, 35]. The austenite and martensite phases can be mediated by heat or tension (See Figure 3). At the macroscopic scale, SMAs show two types of behavior: shape memory and super-elasticity. The shape memory effect requires a minimum temperature for returning to its former shape. The super-elastic effect provides reversibility of total deformation of SMAs under a minimum required temperature. The mechanical properties of the Nitinol used in the current study are presented in Table 1. The stress-strain curve for the Nitinol SMA is presented in Figure 4. In the current study, the area, A_{SMA}, and length, L_{SMA}, of the corresponding SMA are calculated as:

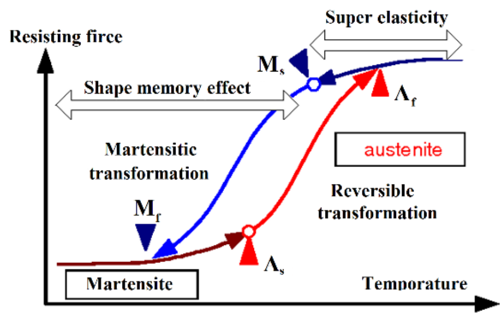


Figure 3. Super-elastic and shape memory effect [32]

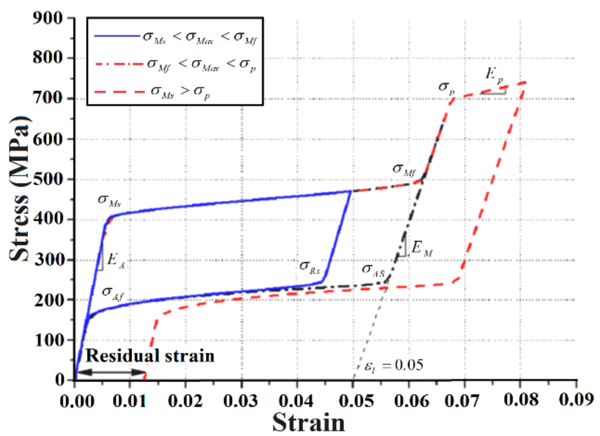


Figure 4. Stress-strain behavior for SMA used in present work [33]

$$A^{SMA} = \frac{F_y}{\sigma_s^{AS}} \tag{2}$$

$$L^{SMA} = \frac{E^{SMA} A^{SMA}}{K} \tag{3}$$

where F_y is the yielding force, K is the axial stiffness and E^{SMA} is the elastic modulus of the SMA material under a stress level of σ_S^{AS} , at which point it enters the inelastic range (i.e., initiates forward transformation).

2. 3. Design of Experiments Determining the design parameters employing experimental analysis by trial and error is time-consuming and costly. FE analysis can lead to reduce costs and overcome design obstacles. The design of experiments (DOE) technique allows process characterization, optimization and modeling in FE simulations [35]. Because it is important to identify the effective parameters and rank them from the highest to lowest priority, the main purpose of DOE is to investigate how the parameters affect the output of the process [36, 37].

In the current study, DOE was performed using response surface methodology (RSM) with a D-optimal design in order to determine the correlation between the outputs and the input parameters. The maximum displacement of the frame and maximum stress were considered as responses. The material properties, diameter and post-tension force applied to the tendons were modeled using the FE method and experiments designed in Design-Expert software. Table 2 shows the values of the parameters. Design Expert determined the design matrices according to the values of the geometric parameters on three levels (1, 0, 1). These design

TABLE 1. Mechanical properties of Nitinol (Ni-Ti) used in the current study [33]

Material properties	Value
Forward transformation stress (σ_{Ms})	400 MPa
Forward transformation stress (σ_{Mf})	500 MPa
Reverse transformation stress (σ_{As})	250 MPa
Reverse transformation stress (σ_{Af})	150 MPa
Plastic stress (σ_P)	700 MPa
Young's modulus (austenite) (E_P)	70 GPa
Young's modulus (martensite) (E_M)	40 GPa
Modulus of plasticity	3 GPa
Maximum transformation strain (ε_L)	5%
Poisson's ratio (austenite)	0.33
Poisson's ratio (martensite)	0.33

TABLE 2. Values of investigated geometric parameters

Parameters	Level		
	1	**0**	**-1**
Tendon material	Steel	-	SMA
Tendon diameter	20mm	12.5mm	5mm
Post-tension force	40kN	20kN	0N

matrices then were used to perform 18 runs of FE data in order to determine a correlation between the input parameters and the responses.

3. RESULTS

In the results of nonlinear static FE analysis on the structure, the validity of the FE model was examined prior to studying the post-tension effect.

3. 1. Validation Since there are no studies available in the open literature that examined the post-tensioning of steel tapered beams. The experimental results of post-tensioning I-shaped beams with steel rebars has been reported by Taoum et al. [20] which is used for validation. The results of the present work were compared with the control beam reported by Taoum et al. [20] and the moment-deflection curve of both results are shown in Figure 5. As illustrated, the FE model predicted the behavior of the I-shaped steel beams with reasonable accuracy at a maximum error of less than 10%. It is concluded that the developed model is capable of studying the performance of the post-tensioned structures.

Figure 6 compares the final deformation of the beam obtained from our FE modeling and the experimental results reported by Taoum et al. [20]. The application of the force resulted in a plastic hinge in the middle section

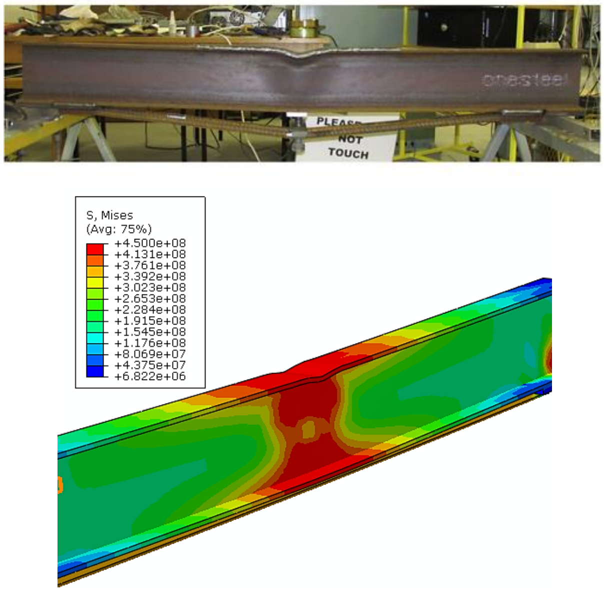


Figure 6. Stress distribution (Pa) of the beam obtained from finite element simulation and the experimental data reported in literature [20]

of the beam in the upper flange and local buckling at the place of loading. Comparison of the FE method and the experimental results for the deformation of the beam revealed that the FE model predicts the deformation of the post-tensioned beam at high accuracy [20].

3. 2. Post-tension with SMA Tendons To ensure that finite element results produce the appropriate accuracy, we conducted a convergence analysis by changing elements size from comparatively coarse to excessively refined meshes i.e. 1mm to 20cm. Figure 7 shows the results for element sizes ranging from 1 mm to 20 cm for sample of No. 1. The results show that elements size of 2 mm is in agreement with an acceptable convergence.

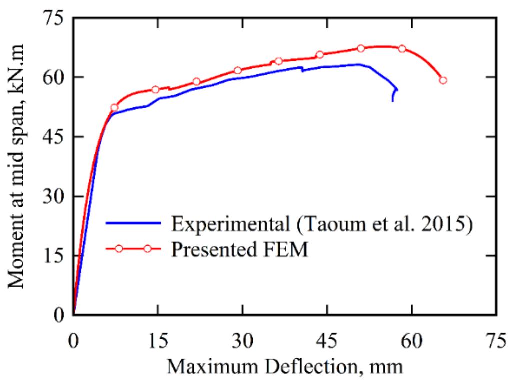


Figure 5. Moment-deflection curve obtained from literture [20] and, the results obtained by the presented finite element model

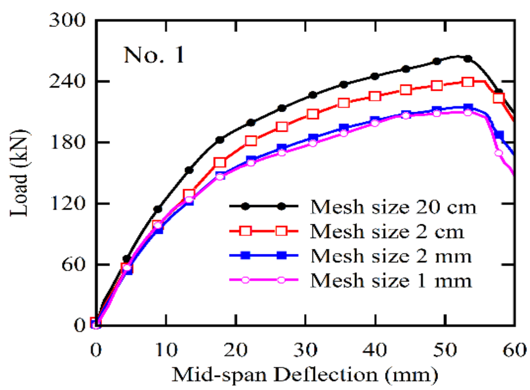


Figure 7. Comparison results between different mesh sizes for sample No.1

Since it was confirmed that our FE model is accurate, it was used to investigate the applicability of SMA tendons to improve the performance of tapered industrial sheds. Figure 8 shows the deformation of steel industrial sheds in samples No. 1, 3, 10, and 12. As listed in Table 3, samples 1 and 3 have been reinforced with SMA tendons with post-tension forces of 10 and 40 kN, respectively. Samples No. 10 and 12 have been reinforced with steel tendons at post-tension forces of 10 and 40 kN, respectively. Figure 8 shows that the maximum displacements in samples No. 1 and 10 were 15.5 cm and 20.4 cm, respectively. Whereas the maximum displacement for samples No. 3 and 12 were 6.8 cm and 10.3 cm, respectively. The SMA tendons caused an increase in the equivalent stiffness of the structure, which decreased the maximum displacement of the structure. The important result of this work is that the displacement of the steel industrial sheds decreased as the post-tension force increased. For example, the SMA tendons with post-tension forces of 10 and 40 kN resulted in 73% and 83% improvement in performance after post-tensioning, respectively.

The load-deflection curves are shown in Figure 9 for three types of steel industrial sheds at a post-tension force of 10 kN; without post-tensioning (sample 0), post-tensioning with SMA tendon (sample 1), post-tensioning with steel tendon (sample 10). As shown in this figure, the load decreased sharply after the peak load for all samples. The results showed that the post-tension approach significantly improved the performance of the steel industrial shed. The load capacity for samples 0, 1 and 10 were 85, 220, and 135 kN, respectively. The SMAs and steel tendons resulted in a 36% and 60% increase in the load capacity of the frame. It was found that the SMA tendons resulted in a two-fold increase in the load-carrying capacity in comparison with steel tendons under equivalent conditions. The performance of the SMA-tendon reinforced frame was similar to that of the steel-tendon reinforced frame in deflections of less than 5 mm.

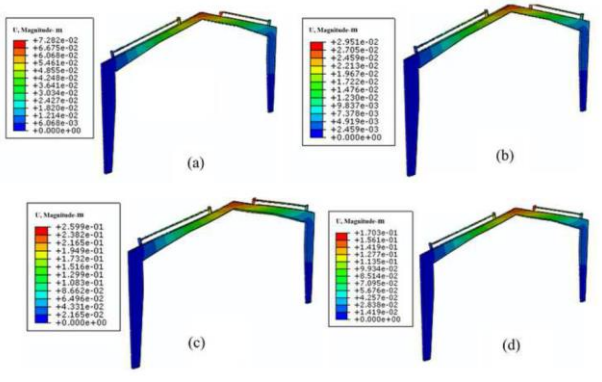


Figure 8. Deformation (m) of steel industrial sheds, (a) No.1, (b) No. 3, (c) No. 10, (d) No. 12.

TABLE 3. Design matrices for modeling geometric parameters

No.	Material	D (mm)	F (kN)
0			0
1			10
2		5	20
3			40
4			10
5	SMA	15	20
6			40
7			10
8		20	20
9			40
10			10
11		5	20
12			40
13			10
14	Steel	15	20
15			40
16			10
17		20	20
18			40

However, an increase in the deflection resulted in a significant increase in the equivalent stiffness of the post-tensioned structure with SMA tendons due to their super-elastic characteristics and the phase change of such alloys under large deflections.

The influences of the effective parameters on the performance of steel industrial sheds based on the experimental design matrices (See Table 3) are presented in Figures 10 and 11. The results revealed that the geometric characteristics and the applied post-tension force also affected the performance of the sheds. In general, an increase in the element diameter and post-tension force significantly increased the load-carrying capacity. At a constant tendon diameter, high post-tension forces did not affect the load-carrying capacity of the frames. For example, for an SMA tendon with a diameter of 5 mm, the load-carrying capacity of the structure increased up to 53% with an increase in the post-tension force from 10 to 40 kN in comparison with samples without post-tensioning. Similar results were observed for post-tensioning with steel tendons. Figure 9 showed that an increase in the post-tension force from 10 to 40 kN for a steel tendon with a diameter of 5 mm increased the load-carrying capacity of the structure by more than 45% in comparison with the sample without post-tensioning. The results also indicated that the post-

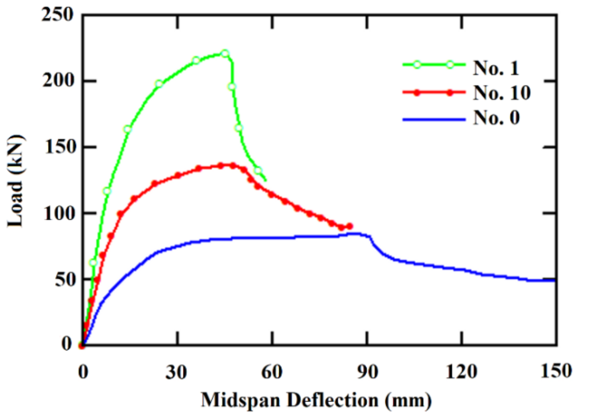


Figure 9. Load-deflection curve for three samples of No. 0, No.1, and No.10

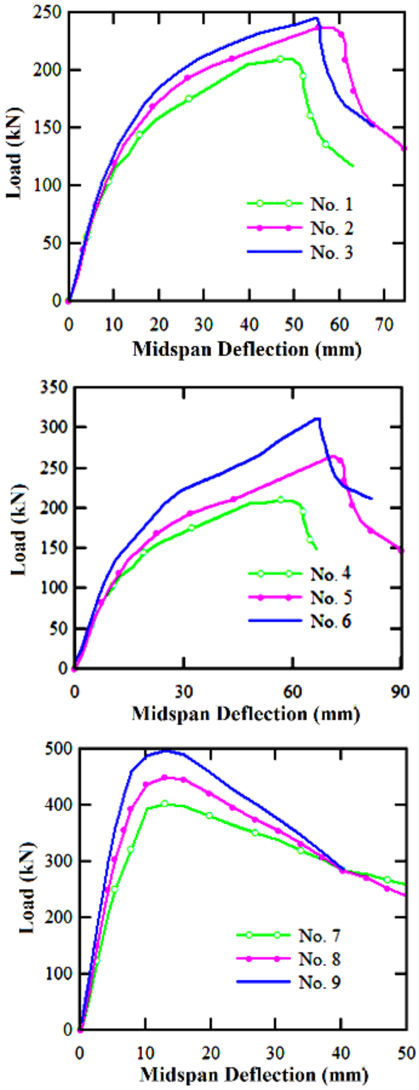


Figure 10. Load-deflection curve for the samples of post-tensioned industrial sheds by SMAs tendons

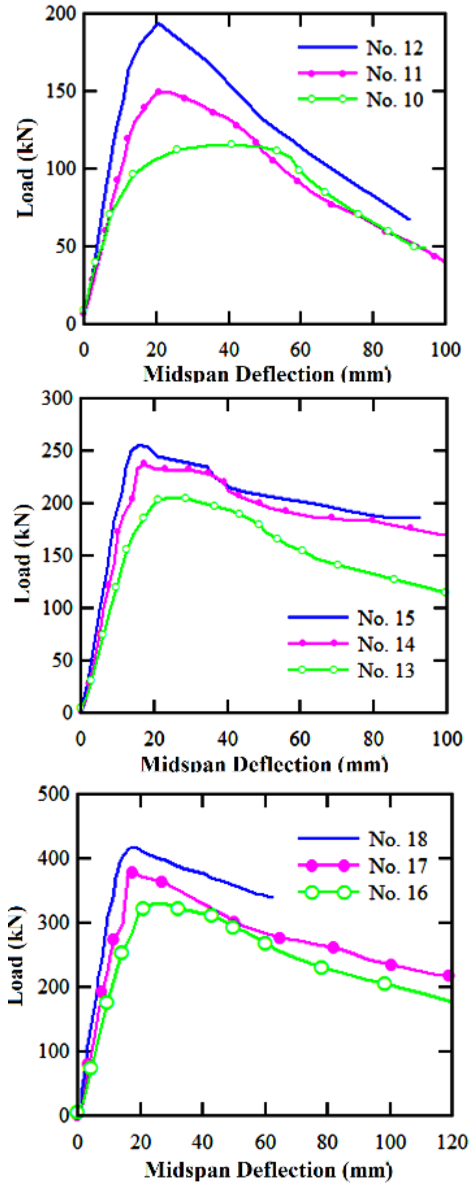


Figure 11. Load-deflection curve for the samples of post-tensioned industrial sheds by steel tendons

tension force is more effective in the SMA tendons rather than the steel tendons.

According to Table 3, samples No. 1 and No. 3 are reinforced with shaped memory tendons with 10kN and 40kN post-tensioning forces, and samples No. 10 and No. 12 are reinforced with steel tendons with 10kN and 40kN post-tensioning forces, respectively. Based on the results, it can be seen that the maximum deflection created in No. 1 and No. 10 samples is 45.5cm and 20.4cm, respectively. Tthese values for samples No. 3 and No.12 are 56.8cm and 20.5 cm, respectively. As can be seen, in the general case, the use of SMA tendons increases the equivalent stiffness of the structure and thus reduces the maximum deflection and deformation created in the structure. The remarkable result is that the effect of SMA tendons on the reduction of steel frame deflection increases with an increase in post-stress force. For example, the use of SMA tendons for post-tension forces equal to 10kN and 40kN increases the performance of using the post-tensioning method by 73% and 83%, respectively, compared to similar samples of steel tendons.

4. CONCLUSIONS

The current study examined the effect of post-tensioning on an industrial shed using local post-tensioning technology and SMA steel tendons. Response surface methodology and design of experiments methods with D-optimal designs were used for the selection of effective parameters. The experimental results on post-tensioned I-shaped beams with steel rebars were used for validation. The FE model was employed to predict the behavior of I-shaped steel beams with reasonable accuracy at a maximum error of less than 10%. The obtained results of the present work indicated that the external post-tensioning method significantly increased the load-carrying capacity of an industrial shed. The SMA tendons increased the equivalent stiffness and decreased the maximum displacement of the structure. They also caused greater improvement in the performance of the structure rather than the steel tendons. The SMA tendons produced a two-fold increase in the load-carrying capacity in comparison with steel tendons under equivalent conditions. The steel and SMA tendons increased the maximum load capacity of the frame 36% and 60%, respectively. The geometric characteristics and applied post-tension force affected the performance of the steel industrial sheds. An increase in the element diameter or post-tension force significantly increased the load-carrying capacity of the sheds. The use of local post-tensioning can improve the performance of structures, decrease the weight of the structure, and also is more cost-effective.

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Persian Abstract

چکیده

آلیاژهای حافظه‌دار شکلی، مصالحی با عملکرد تابع شرایط اعمال بار و تغییرشکل بوده و می‌توانند تغییرشکل‌های بزرگ را تحمل نمایند. در اعضای متشکل از این مصالح، عضو با از بین رفتن تنش ایجاد کننده تغییرشکل، به حالت اولیه خود بر می‌گردد. از آلیاژهای حافظه‌دار شکلی برای تقویت و بهبود رفتار و پایداری سازه‌های فولادی استفاده می‌شود. در مطالعه حاضر به بررسی اثر پس کشیدگی موضعی به منظور افزایش ظرفیت باربری قابهای شیب‌دار فولادی با استفاده از میله‌های فولادی و میله‌های ساخته شده از آلیاژهای حافظه‌دار شکلی پرداخته شده است. به این منظور، از نرم افزار آباکوس برای پیش بینی مقاومت خمشی و ظرفیت باربری قابهای شیب‌دار فولادی تقویت شده با این دو نوع مصالح، استفاده شده است. در مطالعه حاضر، تاثیر قطر و مقدار نیروی پس‌تنیدگی اعمال شده به میله‌های فولادی و تاندون‌های متشکل از آلیاژهای حافظه‌دار شکلی مورد بررسی قرار گرفته است. نتایج حاصل نشان می‌دهد که پس‌تنیدگی خارجی با استفاده از تاندون‌های آلیاژهای حافظه‌دار شکلی، روشی موثر برای افزایش ظرفیت باربری قابهای شیب‌دار فولادی است. میله‌های فولادی و تاندون‌های آلیاژهای حافظه‌دار به ترتیب باعث افزایش 36 و 60 درصدی در ظرفیت باربری قابها و بهبود عملکرد قابهای شیب‌دار فولادی با پس‌تنیدگی موضعی می‌شوند. همچنین استفاده از پس‌تنیدگی موضعی سبب کاهش وزن قابها می‌گردد.