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Numerical analysis on Pre-Stressed Steel I-Beams

Hazem Samih Mohamed

Abstract: ***Pre-stressing with external tendon is one of the most efficient techniques for rehabilitation of existing structures, strengthening of steel structures, controlling the structure deflection and reduction of the construction cost. This paper consisting of a parametric study to investigate the effect of several parameters on the structure behavior. The key variables examined were the number of deviator, eccentricity of the external tendon, pre-stressing technique. ANSYS software has been used to analyze and simulate the process of applying the pre-stressing force and the structure loads. Geometrical imperfections and buckling modes of the unloaded beam are taken into consideration as an initial condition. The results show that these variables impose additional challenges on the accurate prediction of pre-stressed steel structures performance during its service life.***

Index Terms: ***Tendon; External pre-stressing; ANSYS; Steel I-beam; Deviator***

I. INTRODUCTION

In recent years, the needs for better designing techniques and economical achieving are motivated the engineers to do numerous researches on the pre-stressing by using external un-bonded tendons. Pre-stressing with external tendon is one of the most efficient techniques for rehabilitation of existing structures, strengthening of steel structures, controlling the structure deflection and reduction of the construction cost [2, 10]. Such pre-stressed steel structures are mainly consisted in subjecting a material to loads which produce stresses opposed to those in operation through the use of external cables. Historically, the Egyptian sailing ship, 2700 B.C, was the oldest pre-stressed structures and the Crystal Palace in London was the first structural application of suing the pre-stressing technique in real construction . In the past decades, few researchers deals with the behavior of steel structures after pre-stressing with external un-bonded tendons. Bradford [3] proposed the use of design charts to calculate the elastic buckling load induced by pre-stressing tendons in I-shaped cross-section steel beams with straight tendons. It should be mentioned the that technique of external pre-stressing is not limited to steel structures. It could be applied to the internally reinforced concrete structures[1, 3, 14, 14, 12] and steel-concrete composite beams [9, 3, 5, 12]. Externally pre-stressing can be also applied to box type structures, arches and cable trusses.

Recently more study have by conducted to understand the performance of pre-stressed steel beam under service loading[1, 1, 2, 5]. For an instant, Michigan Department of Transportation analyzed the service life of pre-stressed steel I-beams against the traditional steel beams. Their results concluded that, the pre-stressed I-beams have longer service life than the traditional steel beam. Ponnada and Vipparthy [5] developed an equation to calculate the deflecting of pre-stressed steel I-beams. Chen, Liu, and Sun [9] studied experimentally the thermal behaviour of the external tendon. The result showed that the thermal expansion of tendon has a direct influence on the tendon tensile capacity during service live of the structure. So, the climate condition must be considered during the design of the tendon cross section and the initial pre-stressing loading. Experimental study on eleven pre-stressed steel I-beams with various conditions had been carried out by Park et al.. His results showed that the yield and ultimate loading of steel I-beams significantly increased by using external pre-stressing. Belletti and Gasperi [9] did a comprehensive parametric study on pre-stressed I-beam. However they considered many effective parameter should be considered during design of pre-stressed steel beam such as the number of deviators, the pre-stressing force and the bracing, they did not compare them with standard cases such as pre-stressed steel beams with different tendon profile and tendon eccentricity with constant number of deviators. For more understanding on the performance of pre-stressed steel girders and because of the high cost of experimental work, there is a need to conduct more finite element analysis, FEA, on the stability of the pre-stressed steel beams within construction and after construction process, service life.

Hence, this study investigated the externally pre-stressing effects on the flexural behaviour and the structural response of long-span simply supported steel I-beam pre-stressed with external un-bonded tendons. A comprehensive parametric study is simulated for understanding the behaviour of the external pre-stressed steel I-beams. Geometrical imperfections and buckling modes of the unloaded beam are taken into consideration as an initial condition to point its effect on the structural behaviour. The effect of several factors on the stability behaviour of pre-stressed beams is conducted in this paper. there are namely, the number of deviator (tendon supports along the beam length), the eccentricity of the external tendon, pre-stressing technique. In each numerical analysis, one parameter is considered to vary while other parameters are held constants in order to isolate the effects of the considered parameter.

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* Correspondence Author (s)
Dr. Hazem Samih Mohamed*, School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan, Hubei, P.R. China 430074; Hubei Key Laboratory of Control Structure, Huazhong University of Science and Technology, Wuhan, Hubei, PR China, E-mail: hs_mohamed@hust.edu.cn

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II. MODELLING OF THE PRE-STRESSED STEEL I-BEAM

Finite element method is adopted in this study to model several steel I-beam pre-stressed with two external un-bonded tendons. Four-node shell element, SHELL181, is used simulate the steel I-beam and the stiffener and three-dimensional spar element, *LINK10,* is used for the

External tendon. While contact elements, CONTA175 and TARGE170, Is used for modeling the lateral restraint resulting from the bracing as shown in table 1. The material properties of the steel I-beam, external tendon and the contact element are summarized in table 1. To pre-stress the external tendon, a tensile force is applied to the tendon then subsequently caused a compression force of commensurate magnitude in the steel I-beam. The two ends of each tendon are locked in position at both ends of the steel I-beam. Geometrical imperfections and buckling modes of the unloaded beam are involved in this study as an initial condition to indicate its influence on the structural behavior.

The buckling analyses are performed on steel I-beam subjected only to its self-weight. The initial imperfection is assumed to be 1/1000 of the steel I-beam span length. The shape of the elastic buckling mode corresponding to the minimum positive Eigen value is used to define the steel beam shape and to define the nodal coordinate of the nonlinear finite-element model in ANSYS as shown in Figure 1.

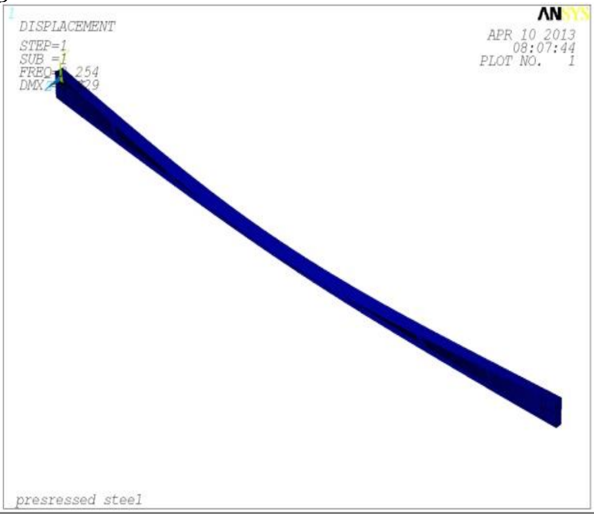

Fig. 1 Buckling Modes of the Unloaded Beam

Used Elements	Parameter	Value
Steel Beam and Stiffeners (shell181)	Yield strength(F_y)	360 N/mm^2
	Young's Modulus (E_s)	200,000 N/mm^2
	Steel hardening (E_t)	0.03Es N/mm^2
	Poisson's ratio (υ)	0.3
External Tendon (link10)	Young's Modulus (E_p)	200,000 N/mm^2
	Yield stress (f_{py})	1680 N/mm^2
	Ultimate stress (f_{pu})	1860 N/mm^2
	Area of external tendon(A_{pe})	1200 mm^2
	Steel hardening (E_t)	0.03 Es N/mm^2
	Poisson's ratio (υ)	0.3
Conta173 & Targe170	Coefficient of friction (μ)	1

Table 1 Material Properties

III. PARAMETRIC STUDY

A simply supported pre-stressed steel plate girder (un-symmetrical section) pre-stressed with external un-bonded tendons as shown in Figure 2 is considered for this parametric study with the following data. Span length of 30 m, Weight per meter = 1451 N/m, Sectional Area A=36400 mm2, Depth of section = 1200 mm, Width of top flange = 400 mm, Width of bottom flange = 300 mm, Thickness of top flange = 30 mm, Thickness of bottom flange = 20 mm, Thickness of web = 16 mm, E = 2 x 10^5 N/mm^2 and unsupported length of 3.75 m. All the beams are designed with two external un-bonded tendons made of steel with a tensile strength f_{pk} = 1860 Mpa and yield strength f_y = 1680 Mpa. Each tendon has a nominal cross-section of 1200 mm^2. The pre-stressed steel I-beams are more prone to deformation in there elastic range than traditional beams as they smaller section area and lesser moment of inertia. Nevertheless, pre-stressing with external un-ponded tendons cause increase the stiffness of the I-beam, decrease the deflection and reduce the construction depth. Hence in the parametric FEA the focused was on the effects of pre-stressing on the deformation on the steel beam in terms of deflection and lateral deformation during the construction stage and after during the service life of the structure.

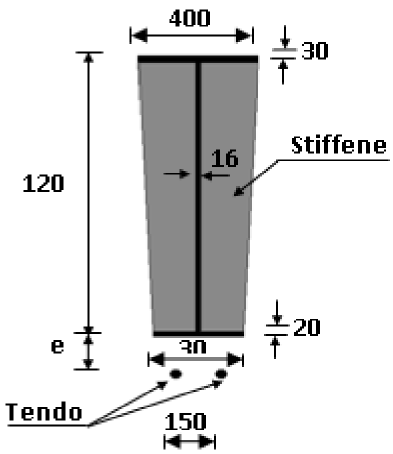

Fig. 2 Details of the steel I-beam used in the Parametric Study

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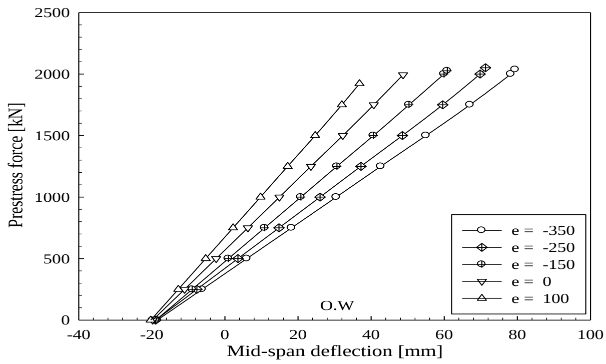
IV. STABILITY OF THE PRE-STRESSED STEEL BEAMS

During construction process, only the pre-stressing force and the self-weight are applied to the beam. There are some factors that have significant effects on the stability of the steel beam and the value of the pre-stressing force. Such as the number of deviators, the eccentricity of the external tendons and the technique of construction (applying the pre-stressing force after bracing or before bracing).

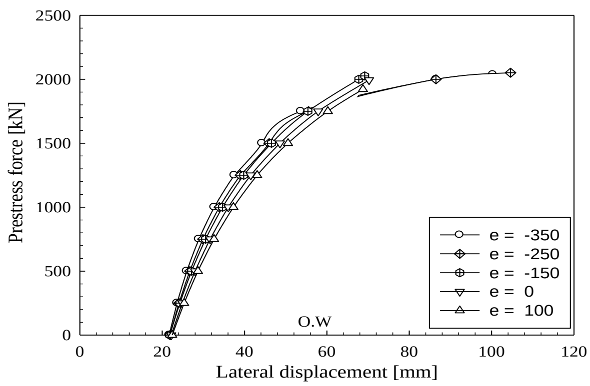
The stability of the structure and the maximum pre-stressing force has been measured by applying the self-weight of the structure and increasing the pre-stressing force in the tendon until the failure occur.

A. Tendon Eccentricity

In order to study the effect of the eccentricity of the external tendons, five pre-stressed steel I-beam with the same number of deviator, three deviators, and different tendon eccentricity are carried out in this section. The values of the eccentricity, e, are 100, 0, -150, -250 and -350 mm. The positive and negative signs of eccentricity, e, mean the tendon deepest point is above and below the deepest point of the steel I-beam, respectively. Figure 3 (a) shows the failure pre-stressing force versus the mid-span deflection for different eccentricity whereas figure 3 (b) shows the pre-stressing force versus the lateral displacement. It can be observed that the ultimate value of pre-stressing forces, which are 2037, 2051, 2026, 1994, and 1922 kN for beams with e = -350, -250, -150, 0 and 100, respectively increases by the increase of tendon eccentricity. Furthermore, at the same pre-stressing force, the beam with high eccentricity has higher reverse mid-span deflection "camber" and lower lateral deformation which lead to increase the carrying capacity of the structure.



(A) Mid-Span Deflection



(b) Lateral displacement

Fig. 3 Influence of Tendon Eccentricity Influence

B. Number of Deviators

The number of deviators is one of the primary items in the design of pre-stressed steel structures. The tensioned cable is in contact at sufficiently regular intervals with the compressed steel beam, the contact point is called "deviator". To study the effect of the number of the tendon deviators on the ultimate value of the pre-stressing force and the stability of the steel beam, four pre-stressed steel beams with the eccentricity e = -150 and a different number of deviators are carried out in this section as shown in Figure 4. The selected numbers of deviators in this section are 1, 2, 3, and 7 deviators. Figure 5 (a) shows the pre-stressing force versus the deflection curves for a different number of deviator whereas Figure 5 (b) shows the pre-stressing force versus the lateral displacement curves. It can be observed that as a result of the increasing the number of the deviator, the stiffness and ultimate pre-stressing force, which are 818, 1063, 2026, and 4822 kN for beams with 1, 2, 3 and seven deviator, respectively increases due to the shape of the tendons compatible with the bending moment diagram of the beam from vertical load as well as more deviators lead to avoid the instability problems caused by increase the lateral deformation.

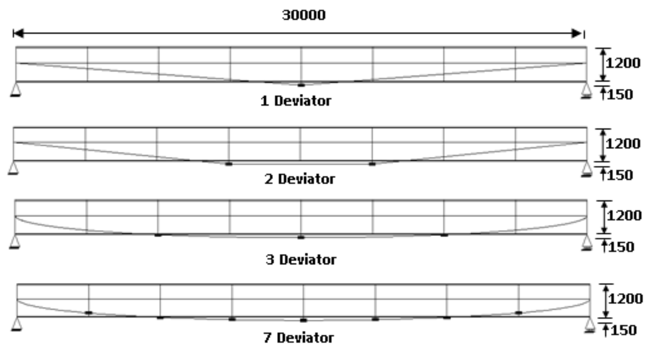
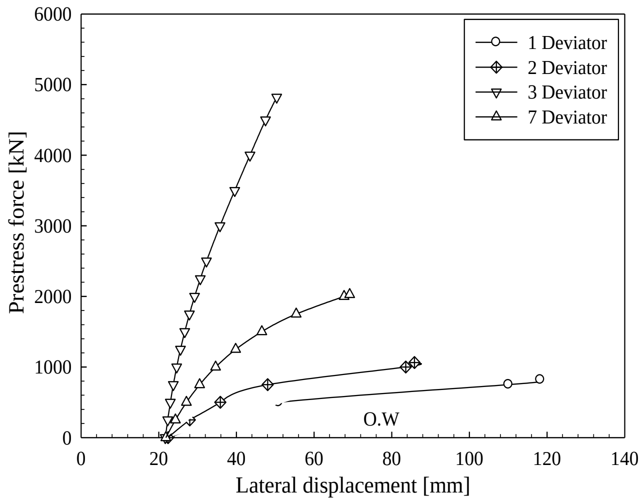


Figure 4 External Pre-stressed steel I-beams with 1 & 2 & 3 & 7 deviators



(a) Mid-Span Deflection

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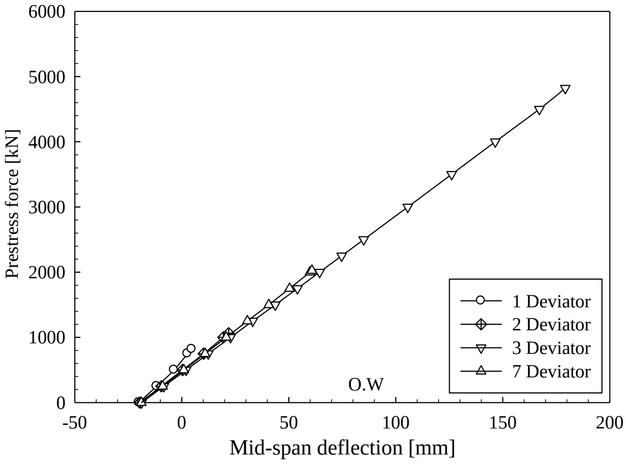
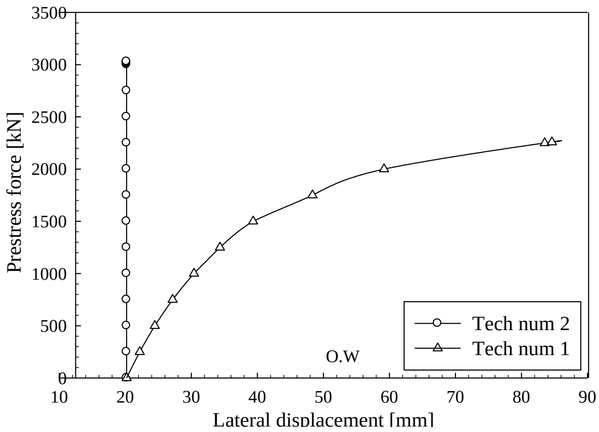


(b) Lateral displacement

Fig. 5 Influence of Number of Deviator

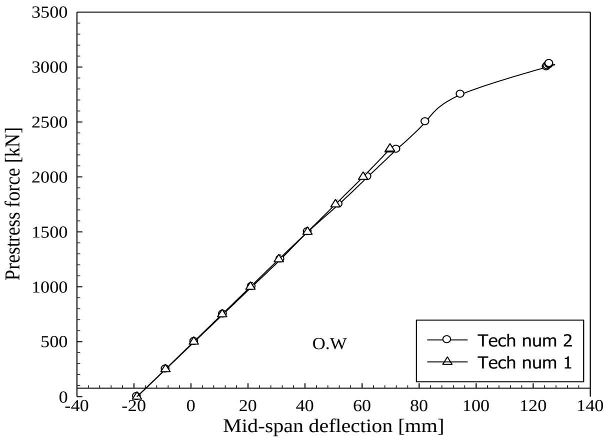


(b) Lateral displacement

Figure 6 Influence of Technique of Construction

C. Technique of Construction

The equilibrium condition for the pre-stressed steel I-beams during the pre-stressing stage is shown in Figure 6. For studying the effect of the construction technique, two pre-stressed steel I-beams with an eccentricity of -150 mm and three deviators are chosen. In the first beam, the pre-stressing force is applied before the connection of bracing whereas in the second beam the force is applied after bracing the beam at top and bottom flange. The external pre-stressing force versus the mid-span deflection curves for the different technique of construction is shown in Figure 6 (a) whereas Figure 6 (b) shows the external pre-stressing force versus the lateral displacement. This figure reveals that the change of construction technique from the first technique to the second technique lead to increase the stiffness and ultimate load capacity. Furthermore, the failure mode in the first technique is due to the instability problem “high lateral displacement” while for the second technique is due to the yield of the steel beam. The ultimate pre-stressing force is increased from 2258 kN in the first technique to 3025 kN in the second technique, by 33.96 %. In summary, bracing elements can reduce the instability effects that take place during pre-stressing of the beam which usually amplified because of geometrical imperfections in the steel I-beam. However, Applying the pre-stressing force on the structure after bracing increases the load capacity but it is not convenient for the practical case because of its difficulty of construction.



(a) mid-span deflection

V. CONCLUSIONS

Nonlinear finite element model conducted by ANSYS to simulate to investigate the influence of pre-stressing on the steel I-beam. Based on the the parametric study, the following conclusions are drawn:

A higher pre-stressing force can be applied if the eccentricity of the tendon increases. Increasing the eccentricity of the tendon cause increase the distance from the neutral axis that leads to high lateral displacement.

A higher pre-stressing force can be applied if the tendon deviator’s increase. The ultimate pre-stressing force is increased from 1922 kN to 2037 kN when the tendons position change from -350 mm to 100 mm because of the shape of the tendons compatible with the bending moment diagram of the structure.

Applying the pre-stressing force after bracing the structure element leads to increase the stiffness, the ultimate pre-stressing force and avoid the instability problems caused by the increase of the lateral deformation.

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