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Finite Element Analysis of the Pre-Stressed Steel Structures

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Abstract: **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. This paper describe a details numerical modelling of pre-stressed steel structures to investigate the effect of several parameters on the structure behaviour. The main objective of the parametric study in this paper is to investigate the performance of the pre-stressed beams at service life of the structure. ANSYS software is adopted in the current study to investigate the process of building the model, applying the pre-stressing force and the structure loads. The results show that a relatively small work effort and can be made very cost effective in comparison to other strengthening methods.**

Keywords: **Tendon; External pre-stressing; ANSYS; Steel I-beam; Deviator.**

I. INTRODUCTION

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 behaviour 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.

Therefore, 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. 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. 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.

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 modelling 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 behaviour. 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.

Table 1 material properties

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

III. PARAMETRIC STUDY

A simply supported pre-stressed steel plate girder (un-symmetrical section) pre-stressed with external un-bonded tendons as shown in Fig. 4 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.

IV. BEHAVIOUR OF PRE-STRESSED STEEL BEAMS DURING THE SERVICE LIFE

This section considers the factor that can affect the steel beam during service stage. The beam is subjected to the pre-stressing force, its self-weight, dead load and live load. For all case studies, the bracing at the bottom and top flanges are applied after applying the pre-stressing force on the external tendon, overall buckling is prevented at the service life. The results have been obtained in this section by using a beam with three deviators and have an eccentricity of -150 mm. The initial imperfection of the steel beam is taken into account (30 mm). The load carrying capacity in the second load phase was measured by applying the own weight of the structure, the pre-stressing on the tendon and increase the vertical load on the beam until failure.

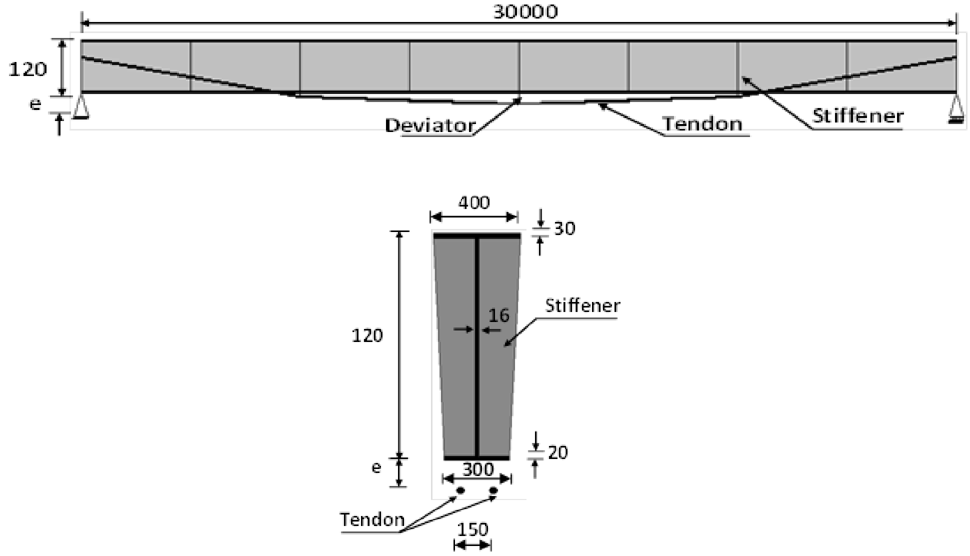

Fig. 1. Details of the steel I-beam used in the parametric study

A. *Service load capacity:*

Five steel I-beams with a different value of pre-stressing force are chosen to study the effect of the pre-stressing force on the flexural behaviour and the ultimate capacity of the structure. The values of pre-stressing force “Ps” are (Ps= 0, 500, 1000, 1500, 2000 kN) taking the geometrical imperfection effects into consideration. All the beams in this section are subjected to a uniform distributed load along its longitudinal axis. Fig. 2 shows the external vertical load versus the deflection for the five steel beams. It can observe that, for an assigned number of tendon deviator’s and the same tendon eccentricity, the load carrying capacity of the steel beam increases from 1596 kN to 1736 kN by 8.77 % by increasing the pre-stressing force in the tendon from 0 kN to 2000 kN. This demonstrates that the pre-stressed steel beams can present both structural and economic advantages compared with traditional steel I-beams.

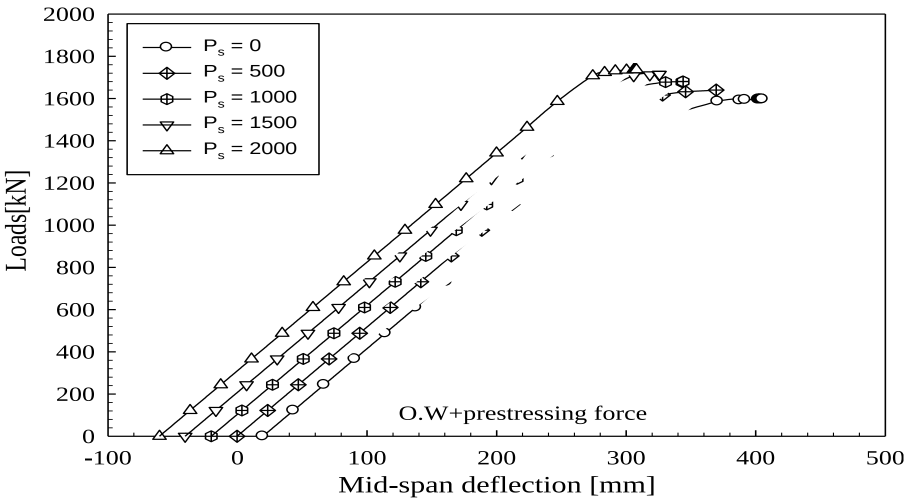

Fig. 2. Service load capacity influence on mid-span deflection

B. Loading type:

The effect of loads application on the loads-deflection response is evaluated by using four types of loads. Namely, single concentrated load at mid span, three concentrated loads "quarter span load", seven concentrated loads and uniform distributed load. Fig. 3 shows that as a result of the increasing the number of the load application point the capacity of the pre-stressed structure will increase. The mid-span deflection of the beam subjected to loads at the quarter span loads (3-point load) is lower than in the beam with a seven-concentrated load (7-point load) because of the shape of the tendons compatible with the bending moment diagram of the beam from vertical loads. Therefore, when the tendons are tensioned, the vertical components of the tendon at the deviators are in the same longitudinal coordinate with the concentrated load and in reverse direction.

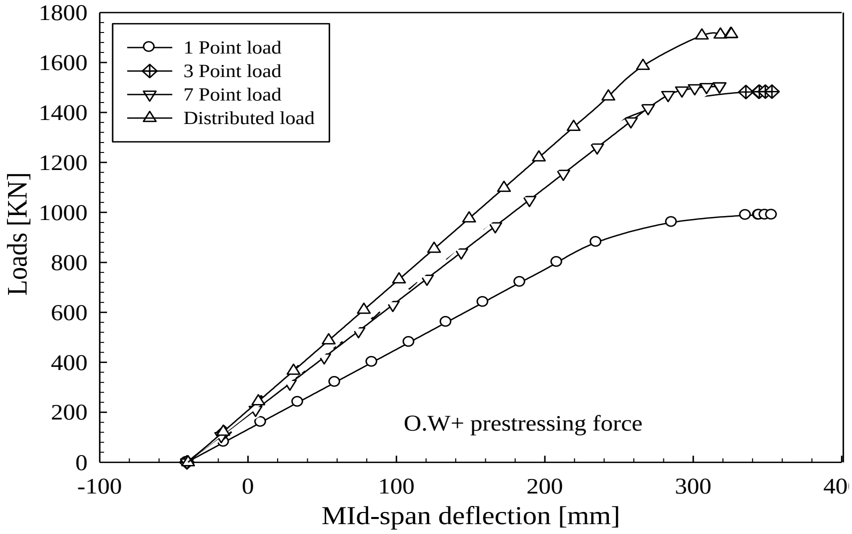

Fig. 3. Loading type influence on mid-span deflection

C. Axial force in the tendon:

The effect of self-stressing force in the external tendons induced because of vertical load application load is explained in this section. It's appearing that the internal forces in the tendon increase with increasing the applied loads. Fig. 4 shows the vertical load versus tendon axial force for the beam with three deviators and pre-stressing force of 1500 kN. As shown in Fig. 4, the effect of imposed load provides a uniform axial force over the initial pre-stressing force applied to the external tendon. The cross-section area of the tendon should choose to make sure that the stress on the tendon won't be greater than the allowable stress.

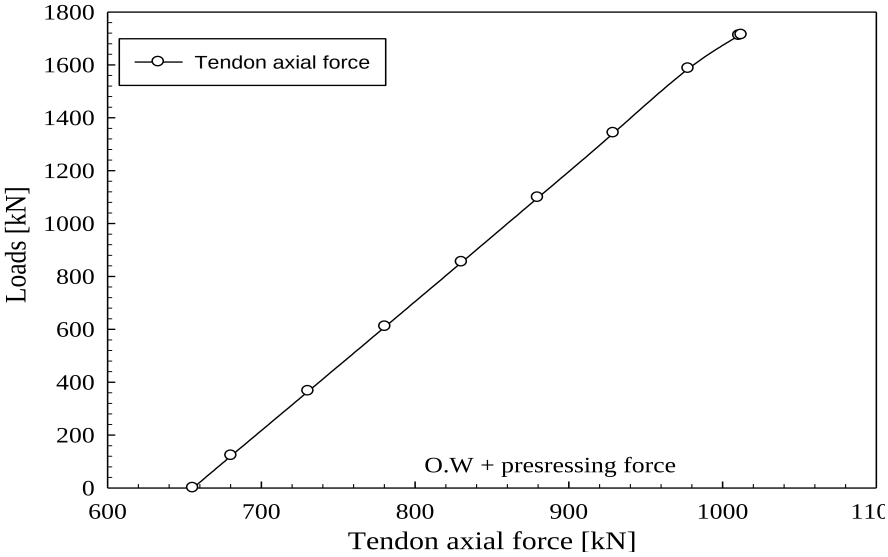

Fig. 4. axial force on the tendon at Service

D. Influence of geometrical imperfection:

To study the effects of geometrical imperfection, two pre-stressed steel I-beam are created to study the effect of the initial imperfection. The first beam assumes to be without initial imperfection whereas the second beam assumes to be with the initial imperfection of 30 mm (L/1000 of the beam span). A pre-stressed force of 1500 kN is applied on the two beams before bracing the steel beam. The load-deflection curves for the two beams are compared as shown in Fig. 5. The initial imperfection has a great effect on the flexure behaviour of the pre-stressed steel structure and must be considered during the design process. The ultimate applying force increases, from 1713 kN in the beam with initial imperfection to 2168 kN in the beam without initial imperfection, by 26.56 %.

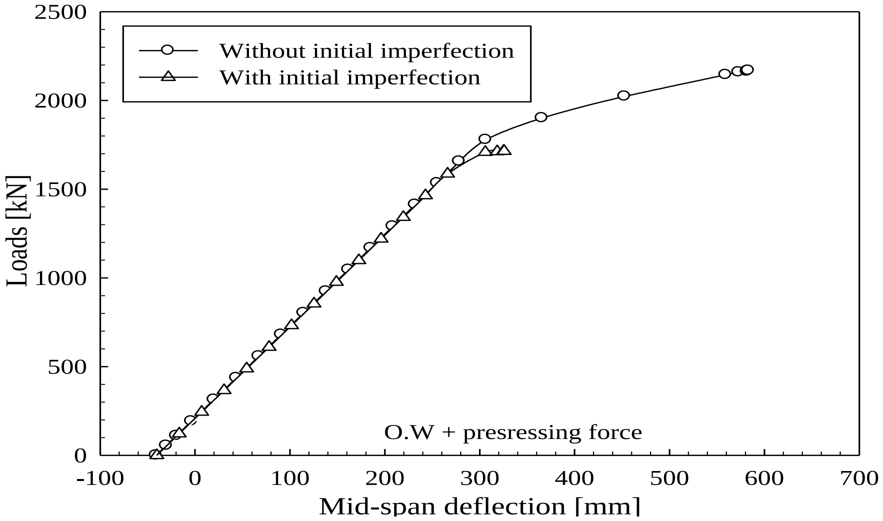

Fig. 5 Influence of geometrical imperfection on mid-span deflection at service

V. CONCLUSIONS

Nonlinear finite element model conducted by ANSYS to simulate to investigate the influence of pre-stressing on the steel I-beam. 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. The results show that a relatively small work effort and can be made a very cost effective in comparison to other strengthening methods. Placing pre-stressed tendons outside a structural member is an effective strengthening method to improve load carrying capacity. Applying the pre-stressing force leads to increase the stiffness, the ultimate service force. By increasing the pre-stressing force and the number of the load application point the capacity of the pre-stressed structure will increase. The effects of self-stressing force provide a uniform axial load over the initial pre-stressing force applied to the tendon.

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