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Research Article

EFFECTS OF STRAND CONFIGURATION ON PRE-TENSIONED I-GIRDERS

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ABSTRACT

The purpose of this paper is to examine the effect of strand configuration on the behavior of precast, pre-tensioned concrete I-girders by considering design load components for highway bridges as dead loads and equivalent lane loads. Under these loads, bridge girder's bottom flange is exposed to tensile stresses. To minimize or eliminate the tensile stresses, compressive stresses are induced in pre-stressed concrete with strands. Determination of strand configuration is important as well as number of strands because it affects stress distribution and displacement of bridge girders. One of the typical precast I-girder with 90 cm height is considered in this study. To determine strand configuration effects, eighteen I-girders with the same cross-section, effective span length and material properties but different strand configuration are selected as an application. Equal prestressing force is applied all strands simultaneously. Three dimensional finite element (FE) models of girder are constituted using ANSYS software. Result of beam theory is used to verify the modeling techniques. At the end of the study, numerically identified stress distribution and displacement for I-girders compared with each other. It is seen that proper strand configuration is effective to reducing stresses and displacements of pre-stressed I-girder.

Keywords: Strand configuration, precast prestressed girder, finite element analysis.

1. INTRODUCTION

Pre-stressed concrete has found extensive application in the construction of medium and long span bridges since the development of prestressed concrete by Freyssinet in the early 1930s because of its better stability, serviceability, economy, aesthetic appearance, structural efficiency, ease to fabricate and low maintenance. The US national bridge inventory (NBI) data shows that the pre-stressed concrete bridges constitute significant portion of the existing bridges in USA. Also in Turkey, the pre-stressed concrete bridges constitute about 53% of the total stock according to General Directory of Highways. These data shows the importance of this type of the bridge design in worldwide. Large numbers of parameters such as girder spacing, cross sectional dimensions of girder, deck slab thickness, number of strands, deck slab reinforcement,

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configuration of stran ds, anchorage system, prestress losses and concrete strength control the design of this bridge type [1].

There are many studies on the design and structural behavior of the pre-stressed concrete in the literature during last two decades. The strand arrangements have significant effects on prestress losses and flexural stresses at various sections along the girder [1]. The effect of deviators and strand configuration on behavior of externally pre-stressed girders is studied by [2]. Debonding strands and changing the order of strand cutting is an effect on cracking mechanism at girder [3] and there is a relation between unbonded strand stress and influential parameters such as amount of strands, amount of mild steel and loading types [4]. The use of high-strength concrete and 0.6-in-diameter (15 mm) strand in the fabrication of precast, pre-tensioned concrete bridge girders has resulted in improved economy through the use of longer spans, increased girder spacing or fewer girder lines and created more shallow superstructures [5]. Horizontal web cracks and inclined cracks are generally thought to induced by the strand distribution in the girder or prestress release procedures [6]. The effect of crack control methods on the tensile strains that cause characteristic cracks at the girder end must be taken into consideration [7]. The region away from the girder end is expected to behave linearly therefore this region can be modeled with linear stress strain relationship [8].

As seen from the references mentioned above, studies on the strand configurations of precast and prestressed concrete bridge girders are insufficient. This paper aims to fill some of these gaps in pre-stressed concrete girder design by making recommendations on the strand configuration to be selected for bottom flange. For this purpose, simply supported eighteen pre-stressed I-girders with same length and cross-section area but different strand configuration is investigated. Girders are numerically modeled based on the finite element method (FEM) using finite element analysis software [9]. The modeling techniques are verified by comparing with the result of beam theory. Once the modeling of the girder is verified, the FE analysis is extended the other girders. The effects of strand configurations on stress distribution and displacements of pre-stressed concrete girders are identified using linear FE analysis.

2. PRE-STRESSED CONCRETE GIRDER MODELS

In this paper, simply supported pre-stressed I-girder with 90 cm height and 24.8 m effective span length is selected as an application. A typical appearance and the dimensions of cross section are given in Fig. 1 and Table 1, respectively. The ultimate strength of concrete (f_c) is taken as 45 MPa. The low-relaxation Grade 270 prestressing strand (characteristic tensile strength f_u of 1860 MPa) 15 mm (0.6 in.) in diameter is selected as a strand type. Strands layout along the girder length is assumed as linear. The distance between strands (5 cm) given by the [10] is used. The modulus of elasticity, passion ratio and density of concrete and strand is taken from [10] (Table 2). Totally eighteen girders which have same cross-sectional area and length but different number of strand and configuration of strand is selected as an application. These girders can be classified into four groups (Table 3).

Table 1. Parameters of girder

Cross-Sectional Dimensions (cm)								
A	B	C	D	E	F	G	H	J
90	50	15	80	10	7.5	50	7.5	15

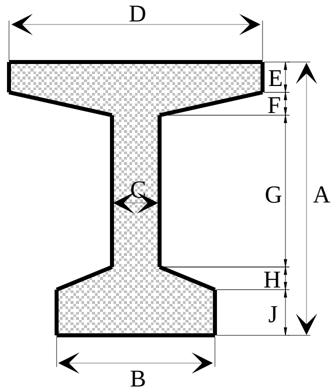

Figure 1. Cross-secti on of the investigated girder

Table 2. Material properties considered in the numerical analysis.

Material	Modulus of Elasticity (MPa)	Poisson's Ratio	Density (kg/m^3)
Concrete	36057	0.2	2500
Strand	197000	0.3	7850

Table 3. Properties of created groups

Group No	Number of girder	Number of strand	Max. number of strand in the first row
#1	5	14	9
#2	5	15	9
#3	4	14	8
#4	4	15	8

The Group #1 consists of five girders with different configuration of 14 strands. The maximum number strand in the bottom row is calculated as 9. The numbers of strand placed in all rows of girder are odd. Strand configurations of the Group #1 girders in bottom flange are illustrated in Fig. 2.

The Group #2 consists of five girders with different configuration of 15 strands. The maximum number of strand in the bottom row is similar to Group #1. The numbers of strand placed in all rows of girder are odd, too. Strand configurations of second group girders in bottom flange are shown in Fig. 3.

The Group #3 consists of four girders with different configuration of 14 strands. The maximum number of strand in the bottom row is calculated as 8. The strands are placed in a row as even number. The bottom flanges of girders of Group #3 are illustrated in Fig. 4.

The Group #4 consists of five girders with different configuration of 15 strands. The maximum number of strand in the bottom row is similar to Group #3. The numbers of strand placed in all rows are even only in girder (c). The other girders rows were different from each other as seen in Fig. 5.

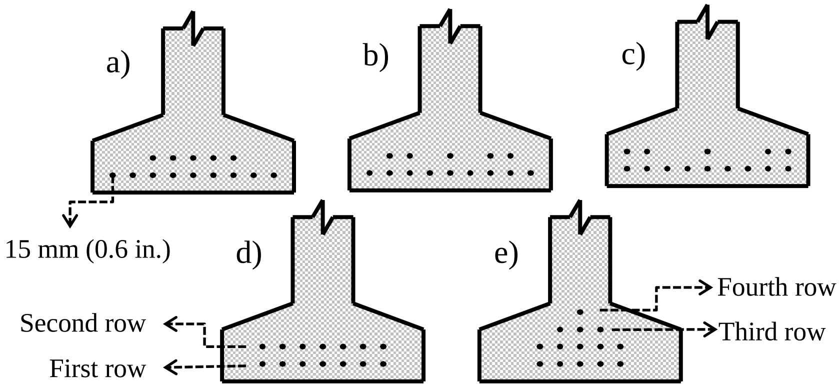

Figure 2. Strand configurations of Group #1

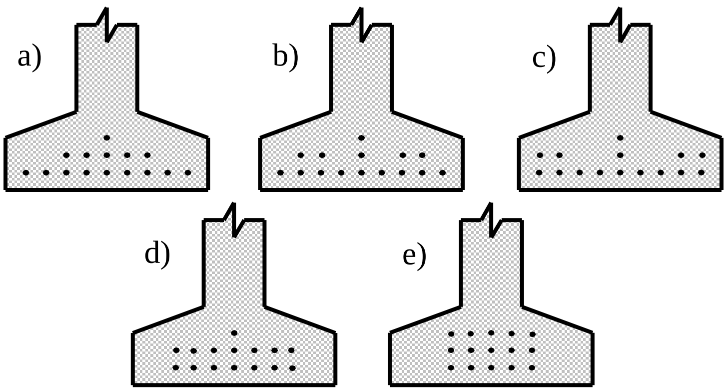

Figure 3. Strand configurations of Group #2

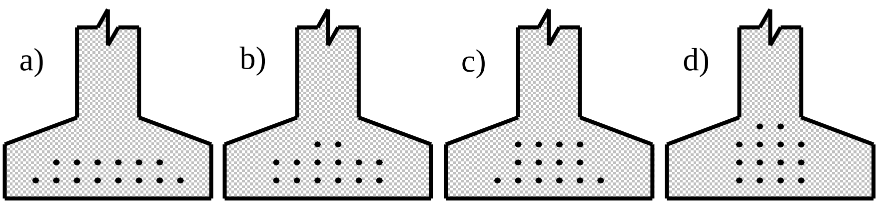

Figure 4. Strand configurations of Group #3

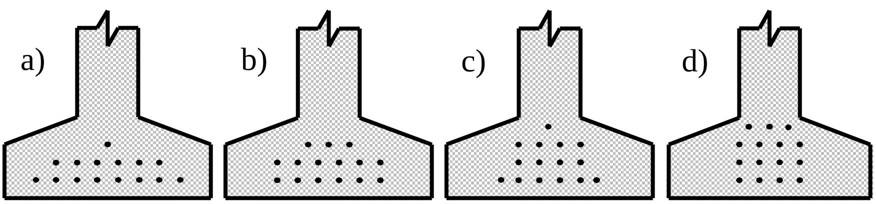

Figure 5. Strand configurations of Group #4

3. FINITE ELEMENT MODELING

The three dimensional (3D) FEM of the selected girders are created by using the finite element analysis software [9] to obtain the stress and displacement distributions. The concrete part of the girders is modeled by using a solid structural element (SOLID65), which is suitable for three dimensional modeling of concrete with or without reinforcing rebar, with the ability of cracking in tension and crushing in compression, as well as the capacity of plastic deformation and creep. The element has eight nodes, and each node has three degrees of freedom namely translations in the nodal x, y and z directions. The strands of girders are modeled using 3D truss element, (LINK180), with two nodes and three degrees of freedom at each node, translations in the nodal x, y and z directions. The strands are assumed to be circular in cross section.

In the FEM the concrete cover is considered as 5 cm. This value is very important in the selecting of mesh size. Since the discrete representation is considered for longitudinal discrete strands and concrete the nodes should be coincided. To this end, concrete and strands are divided by the same mesh sizes as 2.5x2.5x10.0 cm at x, y and z direction, respectively (Fig. 6). Adjacent nodes between the solid and link elements are connected to each other to represent the perfect bond assumption. As a boundary condition, the left and right hand supports are selected as pinned and roller, respectively.

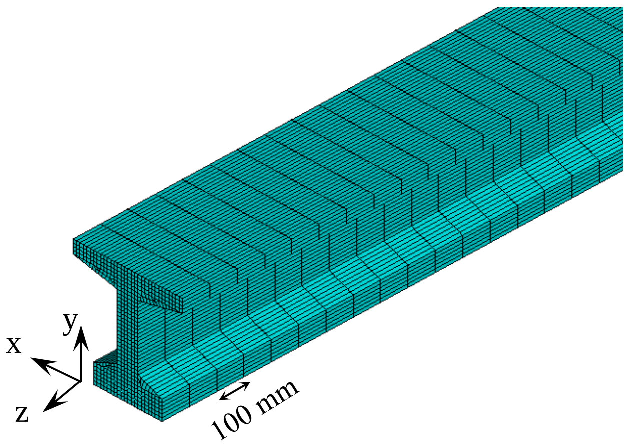

Figure 6. Finite element model of the girder

The design load components for highway bridges can be classified as dead loads, live loads, dynamic loads, environmental condition effects and some extreme events such as collision and braking. In this study, only the first two load components are considered. The dead load mainly consists of the self-weight of structural and non-structural elements. Self-weight of girder is calculated from finite element software directly. The other loads considered in the analysis are shown in Table 4. Equivalent lane load covers forces produced by vehicles moving on the bridge.

According to [10] prestressing force is calculated as 195510 N and applied to each strand. This force is simultaneously applied to the all strands at both sides (Fig. 7).The effects of sudden strands cutting process and the losses of prestress are neglected to estimate the highest stresses that could occur on a girder and to understand the impact of strand configurations alone on girders.

Table 4. Considered loads cases in the analysis

Applied distributed loads (N/m)	
Dead loads of structural elements	7170
Dead loads of non-structural elements	5230
Equivalent lane load	5200

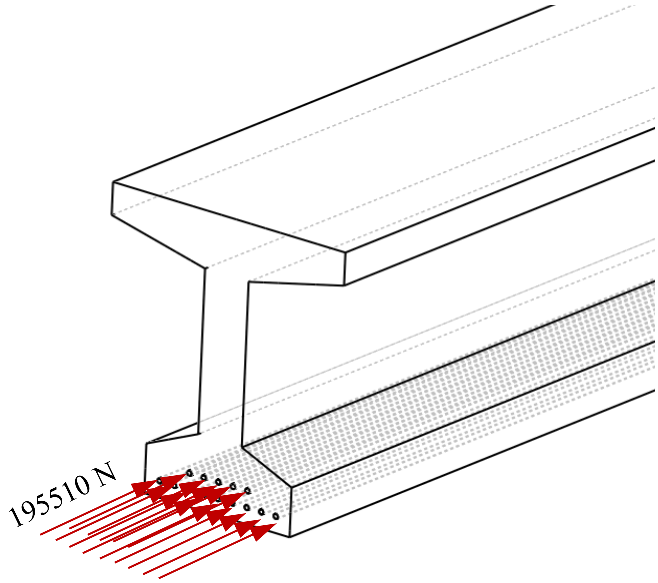

Figure 7. Prestressing force for each strand in the girder

Verification of Finite Element Models

Results of the FEM, which included prestress, dead and equivalent lane loads, are first verified by comparing the linear stresses at the top and bottom of the pre-stressed concrete girder to ones calculated using the beam theory. The results and error in models are reported in Table 5.

Table 5. Verification of FEM using the beam theory

Girder	Concrete fiber location	Stress, MPa		Error %
		Beam theory	FEM	
Group #1 (a)	Top	-19.868	-19.853	0.08
	Bottom	2.860	2.794	2.31
Group #2 (a)	Top	-19.635	-19.678	0.21
	Bottom	1.150	1.255	8.36
Group #3 (a)	Top	-19.995	-19.986	0.05
	Bottom	3.009	2.947	2.06
Group #4 (a)	Top	-19.771	-19.810	0.08
	Bottom	1.291	1.405	8.11

4. NUMERICAL RESULTS

In this section, the maximum and minimum principal stresses distribution and maximum values of displacements in each girder under dead and equivalent lane load are obtained and presented with detail.

4.1. Principal Stresses

The minimum principal stress contour diagram of girder (a) in Group #1 is shown in Fig. 8. This stress contour represents the distribution of the peak values reached by the minimum principal stress at each point within the section. The minimum principal stresses are obtained as 2.79 MPa on bottom flange of the girder at mid-span.

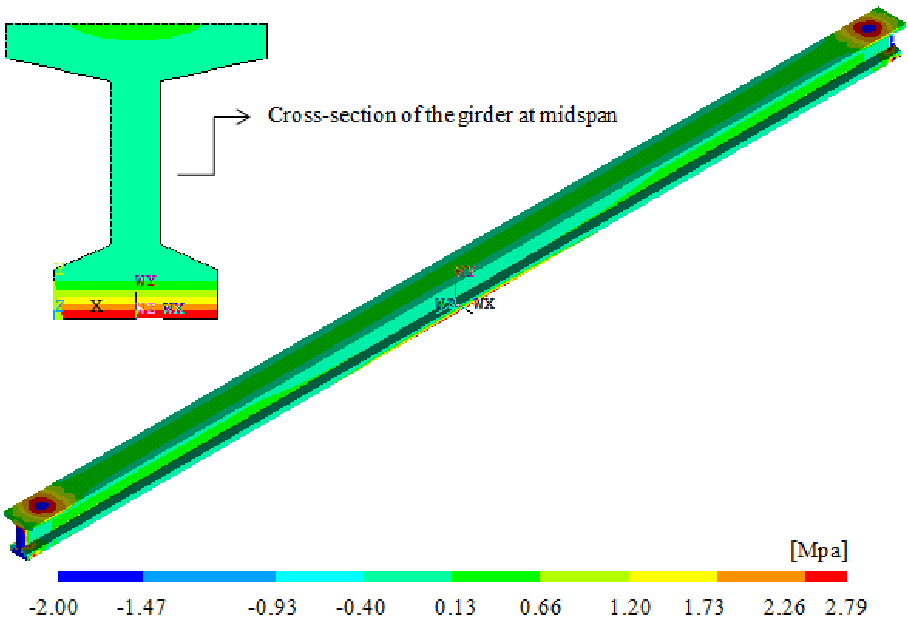

Figure 8. The minimum principal stress contour for girder (a) in Group #1

Cracks are often regarded as undesirable phenomenon in pre-stressed concrete, because they may increase corrosion of embedded strands. Engineers strive to limit the crack in order to prevent reduction of serviceability and durability. Major design codes for pre-stressed concrete structures restrict tensile stress on concrete to prevent cracking.

In this study tensile stress limit of concrete is taken from [10] According to this provision, the allowable concrete tensile stress in MPa is $0.5\sqrt{f'_c}$ for components with bonded prestressing strands or reinforcement that are subjected to not worse than moderate corrosion conditions, where f'_c is the concrete cylinder strength. The allowable concrete tensile stress is taken as $0.5\sqrt{f'_c}$ and the limit of allowable concrete tensile stress is shown with dashed line in the graphics. Fig. 9 points out tensile stress variation on bottom flange of girders at the mid-span for all girders in four groups.

Group #1 consists of five girders with different configurations of 14 strands (Fig. 2). In this group, tensile stresses of bottom flange have an increasing trend from (a) to (e) girder. The maximum tensile stresses are obtained between 2.7939 MPa and 4.1768 MPa. The number of strand and configuration in first row of girder (a), (b) and (c) are equal with each other. The number of strand exist in second row of these girder are also same but the configuration is different. Obtained tensile stresses in these girders are slightly different from each other. When the tensile stresses are examined in Group #1, it is seen that tensile stress obtained from girder (e) exceeded allowable tensile stress limit of concrete and should not be used in design.

Group #2 consists of five girders with different configurations of 15 strands (Fig. 3). In this group, tensile stress of bottom flange have an increasing trend from (a) to (e) girder. The maximum tensile stresses are obtained between 1.2545 MPa and 2.4671 MPa. The number of strands and their configurations in the first and third row of girder (a), (b) and (c) are equal with each other. The numbers of strands in second row are also same but the configuration is different. Obtained tensile stresses in these girders are slightly different from each other. It can be seen from Fig. 9 that all stresses are smaller than allowable tensile stress limit of concrete.

Group #3 consists of four girders with different configurations of 14 strands (Fig. 2). In this group tensile stress of bottom flange have an increasing trend from (a) to (d) girder. The maximum tensile stresses are obtained between 2.9471 MPa and 4.7987 MPa. When the tensile stresses are examined on bottom flange of girders in Group #3, it is seen that tensile stress obtained from girder (b), (c) and (d) exceeded allowable tensile stress limit of concrete. Only first configuration can be used for safety design.

Group #4 consists of four girders having different configuration of 15 strands (Fig. 2). In this group tensile stress of bottom flange have an increasing trend from (a) to (d) girder. The maximum tensile stresses are obtained between 1.4055 MPa and 3.3837 MPa. It can be seen from Fig. 9 the tensile stress obtained from girder (d) exceeded allowable tensile stress limit of concrete and should not be used in design.

The maximum principal stress contour diagram of girder (a) in Group #1 is shown in Fig. 10. This stress contour represents the distribution of the peak values reached by the maximum principal stress at each point within the section. The maximum principal stresses are obtained as 19.853 MPa on the top flange of the girder at mid-span. Maximum principal stresses at top flange of other girders are shown in Fig. 11. The compressive stress limit of concrete for girders is taken $0.45 f_c$ according to [10] where f_c represents specified compressive strength of concrete.

In the Group #1 and Group #2 the compressive stresses of girders have an increasing trend from girder (a) to (e). The maximum compressive stresses are obtained between 19.853 MPa and 21.048 MPa for Group #1, 19.678 MPa and 20.734 MPa for Group #2. It is seen that the compressive stresses of girder (e) are higher than compressive stress limit of concrete for both groups.

In the Group #3 and Group #4 the compressive stress of girders has an increasing trend from girder (a) to (d). The maximum compressive stresses are obtained between 19.986 MPa and 21.581 MPa for Group #3, 19.810 MPa and 21.525 MPa for Group #4. It is seen that the calculated stress values for girder (a) in Group #3 and Group #4 are lower than allowable limit. Only first configuration can be used for safety design.

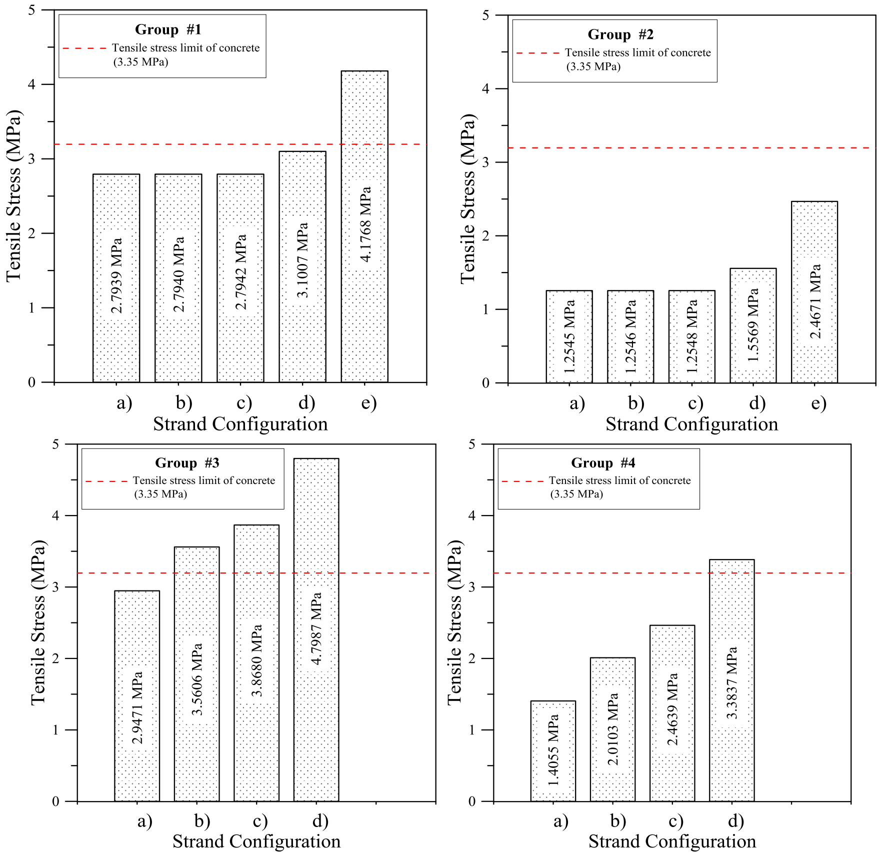

Figure 9. The maximum tensile stresses of girders at mid-span.

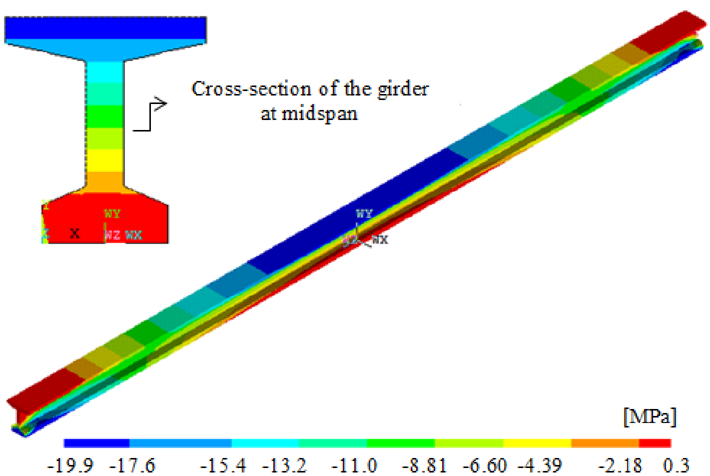

Figure 10. The maximum principal stress contour for girder (a) in Group #1

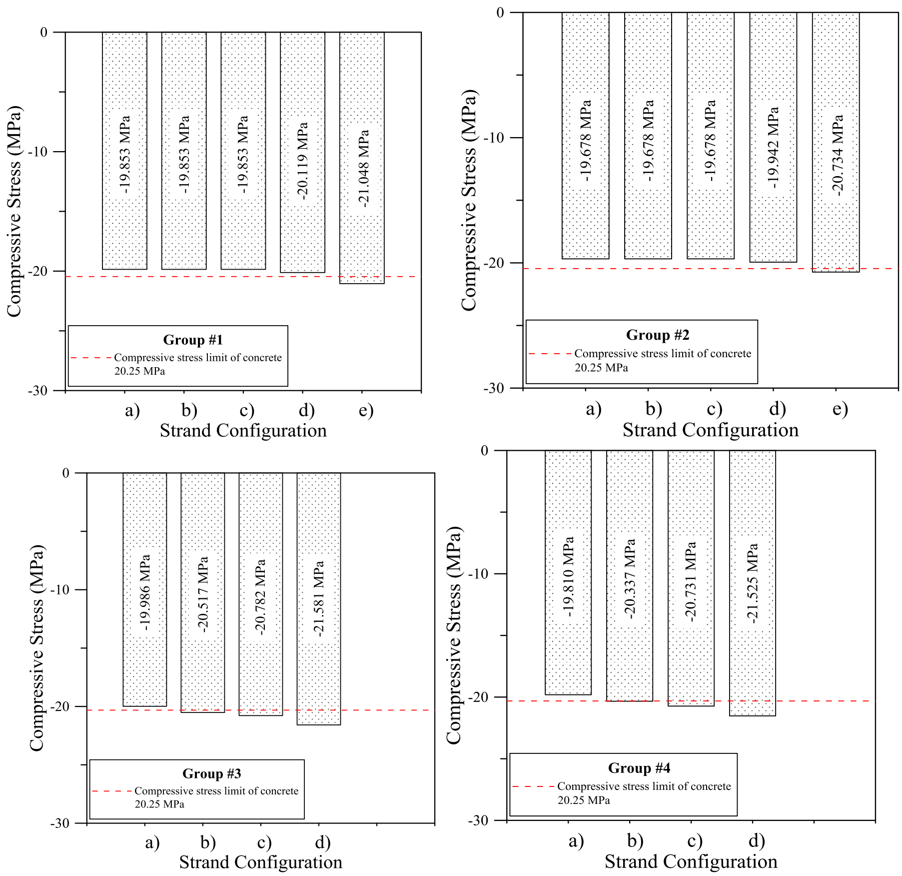

Figure 11. The maximum compressive stress of girders at mid-span

It is seen that the displacements of Group #1 and #2 girders have an increasing trend from girder (a) to (e). The maximum displacements are obtained between 35.6 mm and 42.1 mm for Group #1, 31.4 mm and 37.0 mm for Group #2.

Also, the displacements of Group #3 and #4 girders have an increasing trend from girder (a) to (d). The maximum displacements are obtained as 36.4 mm and 44.9 mm for Group #3, 32.2 mm and 41.2 mm for Group #4.

4.1. Displacement

The maximum displacement contour diagram of the girder (a) in Group #1 is shown in Fig. 12. These contours represent the distribution of the peak values reached by the maximum displacements at each point within the section. The displacement values increase along to the middle of the girder span and the maximum displacement is obtained as 35.6 mm at the mid-span of the girder. The maximum displacement values obtained from bottom flange of girders at the mid-span for all girders are plotted in Fig. 13.

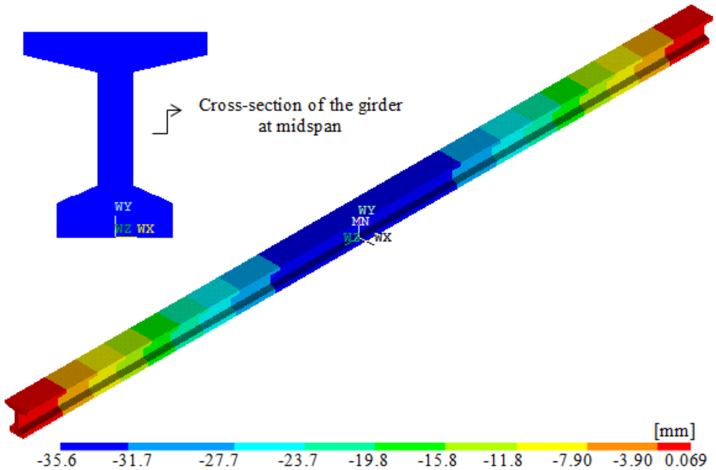

Figure 12. The maximum displacement contour of the girder (a) in Group #1

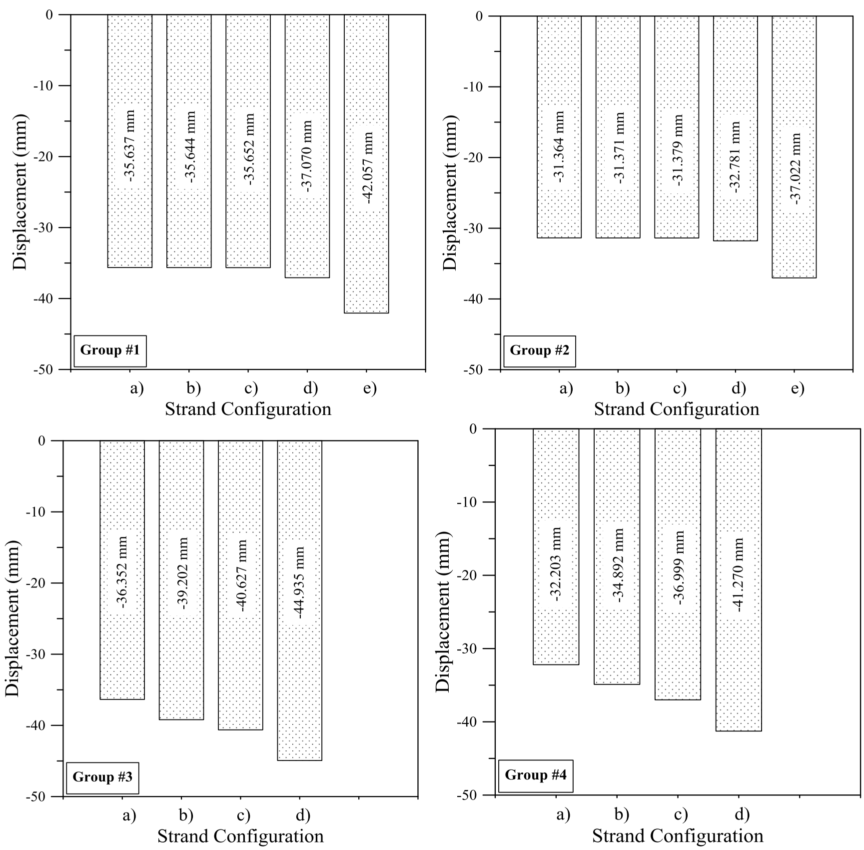

Figure 13. The maximum displacements of girders at mid-span

4. CONCLUSION

This study presents an investigation study about the effect of strand configuration on structural behavior of pre-stressed concrete I-girders. Eighteen girders with same cross-section, effective span length and material properties but different strand configuration selected as an application. 3D FE model of girders are constituted by using [9]. Analysis of girders is performed under dead loads of structural and non-structural elements and equivalent lane loads. Displacement and stress distribution of girders under these loads are compared with each other. The main conclusions drawn from this analytical study are:

- The tensile stresses on the bottom flange of the girders are decreased as 33%, 49%, 39% and %58 with different strand configuration in Group #1, Group #2, Group #3 and Group #4, respectively.
- The compressive stresses on the top flange of the girders are decreased as 6%, 5%, 7% and %8 with different strand configuration in Group #1, Group #2, Group #3 and Group #4, respectively.
- The strand configuration on stresses obtained from bottom flange of girders is more effective than top flange stresses of girders.
- The displacements of the girders are decreased as 15%, 15%, 19% and %22 with different strand configuration in Group #1, Group #2, Group #3 and Group #4, respectively.
- The strands which are placed closer to the symmetry axis of the girder in the same row help to decrease the maximum and minimum principal stresses.
- The maximum and minimum principal stresses occurring on the girder decreases when the distance gets closer from strands to bottom fiber of girder.

It is seen that proper strand configuration is effective to improve structural behavior of girder such as maximum and minimum principal stresses and displacement. To determine proper strand configuration of precast, pre-tensioned concrete bridge girders has resulted in improved economy through decreased number of strand and shallower superstructures.

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