ARPN Journal of Engineering and Applied Sciences

OPTIMUM DESIGN OF VERTICAL STEEL TENDONS PROFILE LAYOUT OF POST-TENSIONING CONCRETE BRIDGES: FEM STATIC ANALYSIS

Ali Fadhil Naser
Department of Building and Construction Engineering, Al-Mussaib Technical College, Al-Furat Al-Awsat Technical University, Babylon, Iraq
E-Mail: ali_hu73@yahoo.com

ABSTRACT

The objectives of this study are to evaluate the optimum design of tendon profile layout, to study the effect of tendon profile layout on the structural performance of post-tensioned concrete bridge model, and to investigate the locations effect of anchorages points of tendons on the vertical deflection. There were four factors were selected such as bending moment, shear force, stress, and vertical deflection. According to supports of tendons, there are two cases of bridges models. The first case is used simply-supported tendons profile layout. The second case is adopted continuous tendons profile layout. According to profile layout of tendons, the first case consists of seven bridge models (7-Models) and the second case includes ten bridge models (10-Models). The results of FEM analysis showed that the tendon profile layout had important effect on the structural performance of post-tensioned concrete bridges according to types and number of anchorages points of tendons. For pre-stressed load stage, simply-supported tendon profile model appeared maximum value of upward vertical deflection (3mm) was more than continuous tendon model (2mm). The maximum downward vertical deflection is 12mm within continuous tendon model which is less than value of simply-supported tendon model (13mm). According to service load stage analysis, continuous tendon model had the minimum value of downward vertical deflection (14mm) was more than simply-supported tendon model (15mm), but maximum value of downward vertical deflection was appeared in simply-supported tendon model (27mm) was more than the maximum value of downward vertical deflection (26mm) within continuous tendon model. It can be concluded that continuous tendon profile model was convenient for design of post-tensioned concrete bridge because it can be resisted service loads and had the lower value of vertical deflection.

Keywords: post-tensioned, tendon, bridge model, profile layout, vertical deflection, bending moment, shear force, stress.

1. INTRODUCTION

A bridge is a significant and competent structure and it involves of numeral of components. These components include two parts. First parts are including the bearings, girders or beams, deck, joints, pavement layers, security barrier, and drainage system. They were known as superstructure. While, the second parts were known as substructure which was consisted of the foundations, piers, and pier caps. Bridge structure can be constructed over an obstruction, such as rivers, highways, railways. Bridges structures can be classified according to materials and types of supports. According materials of construction, the types of bridges include concrete bridges, pre-stressed concrete bridges, wood bridges, and steel bridges. For types of supports, the bridges structures include simply supported bridges and continues bridges [1, 2, 3, 4].

The system of pre-stressed concrete bridge deals with the applied of tendons loads before the application of the service loads (traffic loads, dead load, temperature load, wind load, and live load) on the bridge structure. Pre-stressed concrete system consists of two types. The first type is pre-tensioning. The second type is post-tensioning. Post-tensioning is a method of concrete structure reinforcement with high strength steel strand or bars referred to as tendons [5, 6, 7, 8].

Post-tensioned concrete system is widely used in the erection of bridges structures because this system provides several advantages over normal reinforcement concrete. Also it contains on more efficient use of materials, better deflection and crack control, durability, quicker construction, reduced cost, and design flexibility. The components of post-tensioned system include wires, strands, ducts, and tendons and corrosion protection equipment. The single wire has diameter which is 0.2 inch and it made of high-strength steel meeting ASTM A416 specifications. Strand has seven wires with a nominal diameter of 0.6 inches. Tendons are containing a group of several strands (structural load-carrying elements) and the cementations grout and duct (non-structural, corrosion-protection elements). Tendons can be classified as bonded and un-bonded tendons. Bonded tendon can be defined as direct contact or bonded to the adjacent concrete. Whereas, un-bonded tendons is not in direct contact with concrete or cannot transfer the stress through the surface bonding. [9, 10, 11].

The strength of tendons depends on the durability of the system materials such as pre-stressed steels, anchorages, ducts, grouted materials, the setting up of these materials, and design concept specifics. The post-tensioning layout and layers of protection such as concrete cover and selected materials in view of the aggressively of the environment for instance [12].

The layout of tendons profile shows an important character in the decreasing of tension stress from concrete. The curvature degree of tendons applies force on the concrete to balance the forces that causing tension stresses. The tendons are located with eccentricities towards the soffit of the beam to stabilize the sagging bending moments due to crosswise loads. Therefore, the pre-stressed concrete beams bend upwards (camber) on the

ARPN Journal of Engineering and Applied Sciences

application of pre-stressed load. The tendons profile will represent the shape of the bending moment diagram when the bending moment is the product of the pre-stressed load and eccentricity [13].

The main objectives of this research are to evaluate the optimum design of tendon profile layout, to study the effect of tendon profile layout on the structural performance of post-tensioned concrete bridge model, and to investigate the locations effect of anchorages points of tendons on the vertical deflection.

2. RELATED PAST STUDIES

The tendon profile layout is important factor in the design of post- tensioning concrete bridges but most studies that deal with tendons profile layout were studied the effects of them on the structural performance for simply normal concrete beams and concrete slab. Therefore, the present paper will be focused on the tendons profile layout design for post-tensioning concrete bridges (simply-supported bridges and continuous bridges).

P. Ng and A. Kwan (2006) noted that the determination of pre-stressed tendon profile is a critical stage in the design of post-tensioning concrete structures. They explained that the load-balancing method provides great probable for direct determination of tendon profile. They used load-balancing method with different considerations in the application of this method and they presented two examples to explain the step-by-step procedures. The results shown that the method is essentially simple to appliance, even in complicated structures like curved continuous bridges. Finally, they concluded that the load-balancing method is a much more efficient alternative to the conventional method and should be incorporated in the standard design process. [14]

A. Ali *et al* (2010) presented the tendons layout design of one-way pre-stressed concrete slabs using finite element method analysis. They used B-Spline method for tendons layout design of pre-stressed concrete slabs. The stresses in the structure were calculated by using finite element method. They stated that the method of modeling tendons as parabola and variable their eccentricities to decrease tension stresses of the concrete lags behind because of the tendons are not truly parabolic especially in continuous structures. The shape of tendons was changed to get the desired profile by varying the ordinates of the B-spline. The tendons layout is developed so that stresses in the structural element be below the limiting tensile stress. According to stresses results of finite element analysis, tendons profile was changed in iterative manner [15].

A. Ali *et al* (2013) presented a new method to design tendons layout of pre-stressed concrete slabs. They were using B-spline to model and account the tendons profile perfectly. They developed efficient algorithm to obtain the tendons layout for pre-stressed concrete slabs. According to finite element computations, tendon and concrete are modeled by using 3 nodes of bar and 20 nodes of brick elements respectively. The tendon- concrete interactions are precisely accounted using vector calculus formulae. They found that the using of proposed technique a two-way pre-stressed concrete slab has been successfully designed considering several design criteria. [16]

C. Kumar and L. Venkat (2013) used the genetic algorithm based optimum design of pre-stressed concrete beams. Their paper deals with the optimization of a simply supported pre-stressed beam subjected to live and dead loads using genetic algorithm method. They studied the cost of tendons and concrete. They were taken cost ratio of tendons to concrete is taken as 8. They considered different factors in the analysis. These factors are the effect of beam length on optimum cost, effect of profile of tendons on optimum cost, effect of population size on cost ratio, effect of live load on optimum cost. The results of analysis showed that the percentage difference in optimum cost between 14m and 15m of beam length is 21.7%. The percentage difference in optimum cost between 50kN/m to 60kN/m of live load is 16.8%. For length of beam is 13m, there is not effect of restraining the tendons profile, but for 14m and 15m of beam lengths, parabolic tendons profile gives higher optimum cost as compared to straight tendons profile. The percentage increase in optimum cost is 4.22% for the parabolic tendon profile when compare to straight tendon profile [17].

P. Colajania *et al* (2013) explained the design procedure for pre-stressed concrete beams. they provided the optimal layout of ordinary reinforcement in pre-stressed concrete beams that subjected to bending moment and shear force. [18]

A. Dixit and V. Khurd (2017), developed three-dimensional finite element modeling of post-tensioning concrete beam that can be used to investigate the effect of eccentricity, pre-stressed load and tendons profile for concentrated point loading. They used ANSYS program in analysis. The results of static analysis showed that the eccentricity, pre-stressed load and tendons profile are important factors and they should be taken into consideration while designing the post-tensioning concrete beam. [19]

K. Abdul-Razzaq *et al* (2018) investigated the structural performance of post-tensioned two-way concrete slabs. with the different bonded tendons layout. They used non-linear finite element analysis method to select the most active and optimum location of tendons layout with different number of tendons and applied load on the concrete two-way slab. They found that the results of analysis showed that the failure load in post-tensioning in both directions increased about 89 % as compared with slab post-tensioning in one direction. [20]

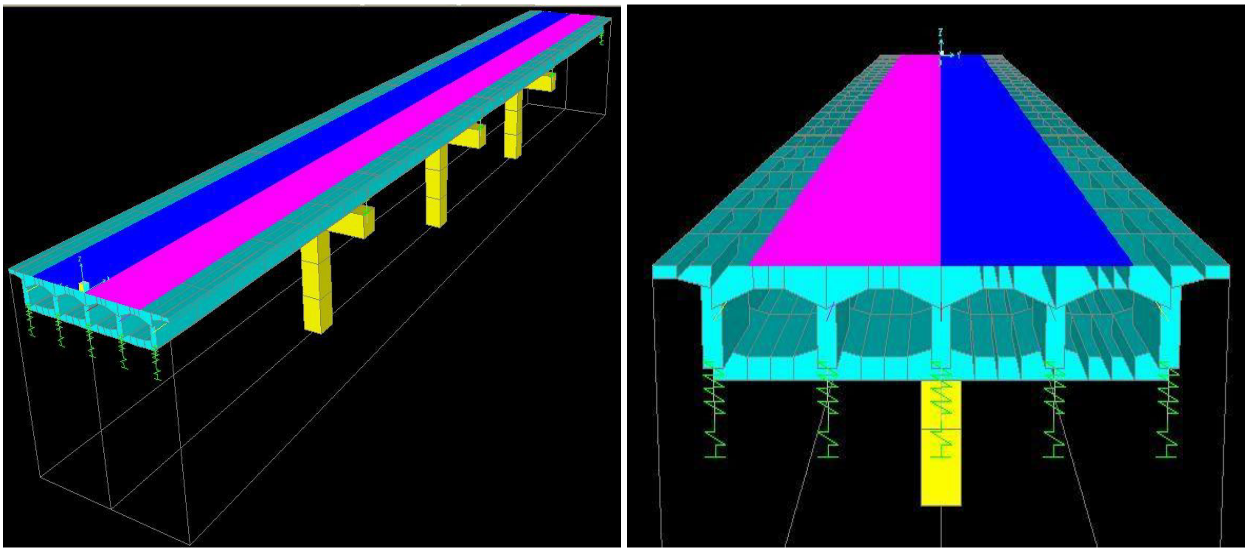
3. BRIDGES MODELS DETAILS

In the present paper, continuous box girder post-tensioned concrete bridge model is selected. There are two cases of bridges models according to supports of tendons. The first case is used simply-supported tendons profile layout (the start anchorage and end anchorage of tendons along each span). The second case is adopted continuous tendons profile layout (the start anchorage and end anchorage of tendons along all spans). According to profile layout of tendons, the first case consists of seven bridge models (7-Models) and the second case includes

VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

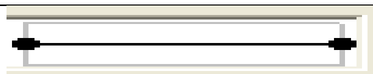
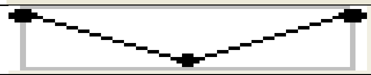
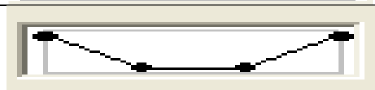
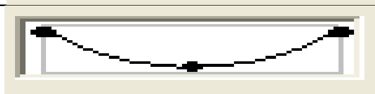
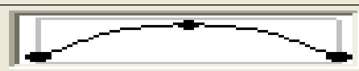
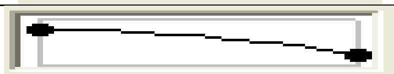
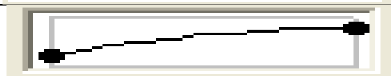
ten bridge models (10-Models). The length of continuous box girder post-tensioned concrete bridge is 80m with four spans (each span length is 20m) and the width is equal to 11m. the load of pre-stressing tendon is same foe all models. Figure-1 shows the longitudinal and transverse bridge model. Table-1 lists the bridge models with profile layout for case 1. Table-2 lists the bridge models with profile layout for case 1.



(a) (b)

Figure-1. The bridge model: (a) longitudinal section, (b) transverse section.

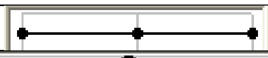
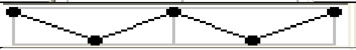
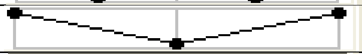
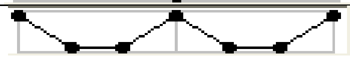
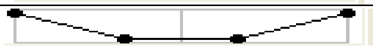
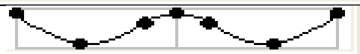
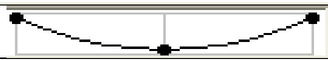
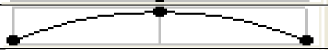
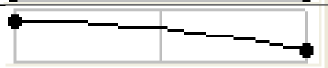
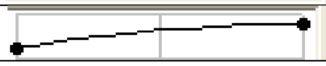
Table-1. The bridge models with profile layout for case 1.

Model no.	**Profile name**	**Layout**
Model No. 1	Straight tendon	
Model No. 2	Straight tendon with two bends	
Model No. 3	Straight tendon with three bends	
Model No. 4	Parabolic tendon with two concave bends	
Model No. 5	Parabolic tendon with two convex bends	
Model No. 6	Parabolic tendon with two points (down-up)	
Model No. 7	Parabolic tendon with two points (upward)	

VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-2. Profile tendon layout for case 2.

Model No.	Profile name	Layout
Model No. 1	Straight tendon	
Model No. 2	Straight tendon with four bends in all spans	
Model No. 3	Straight tendon with two bends in all spans	
Model No. 4	Straight tendon with six bends in all spans	
Model No. 5	Straight tendon with three bends in all spans	
Model No. 6	Parabolic tendon with four concave bends in all spans	
Model No. 7	Parabolic tendon with two concave bends in all spans	
Model No. 8	Parabolic tendon with two convex bends in all spans	
Model No. 9	Parabolic tendon (down-up) in all spans	
Model No. 10	Parabolic tendon (upward) in all spans	

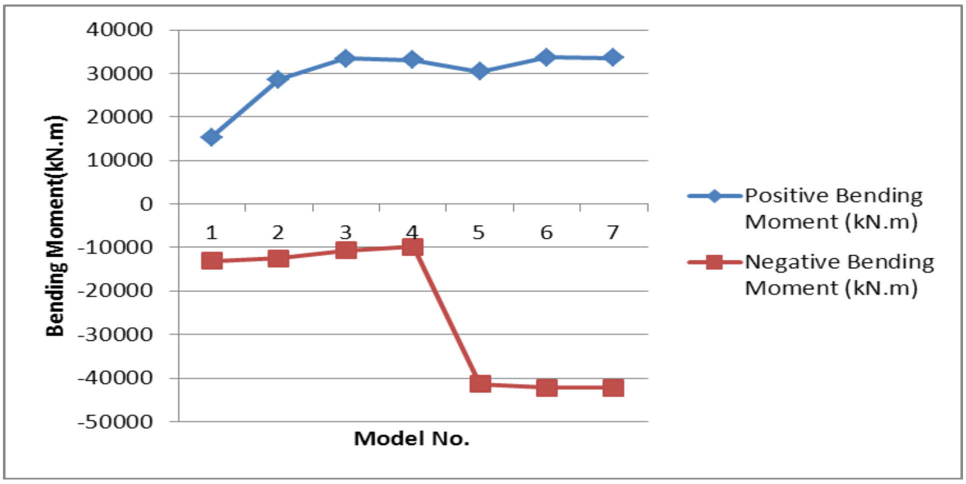
4. RESULTS OF FEM ANALYSIS

Tendons profile layout is an important factor that is effected the static behavior of post-tensioned concrete bridges. Sap2000 program is used in the FE Analysis of bridges models. Static analysis is adopted to evaluate the optimum design of tendons profile layout. The FE Analysis is used to calculate the positive and negative bending moment, shear force, tensile and compressive stresses, and vertical deflection. There are two stages of internal design loads for each case of analysis. These stages are pre-stressed load and service loads (combinations of loads).

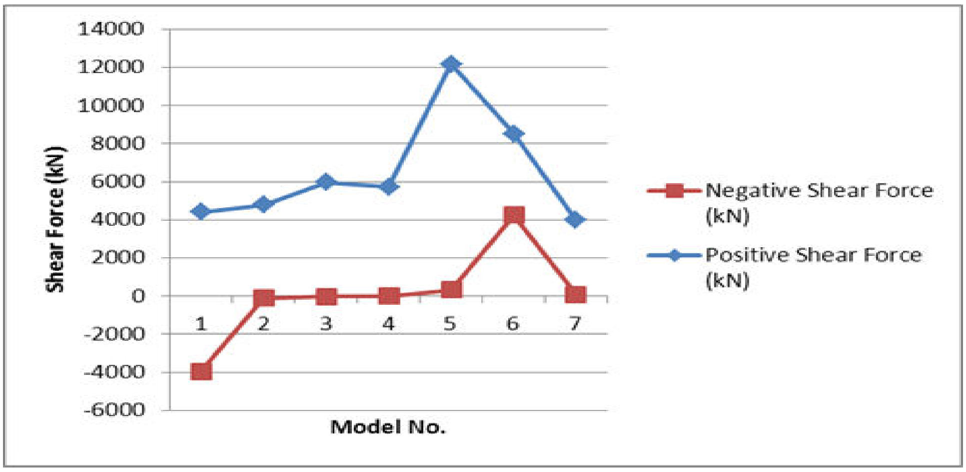
4.1 FEM analysis of simply-supported tendons profile layout (case 1)

4.1.1 Pre-stressed load stage

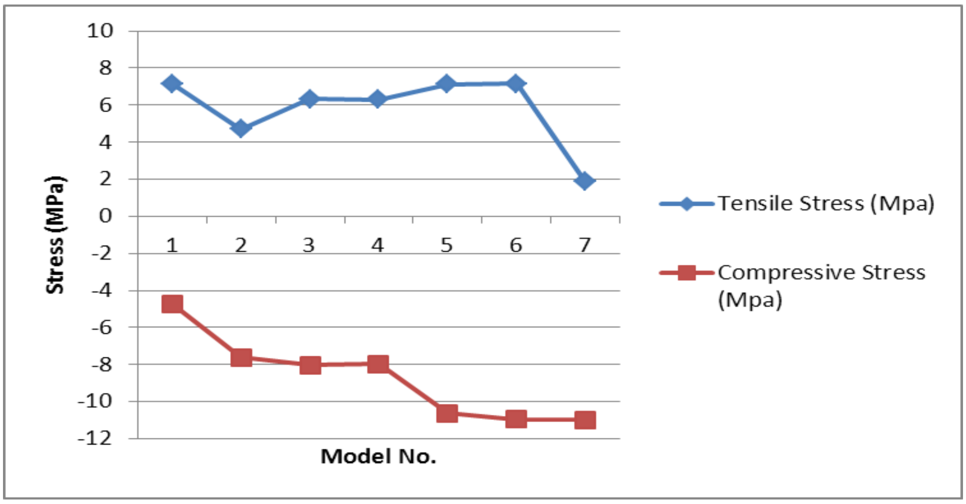
The results of pre-stressed load stage for case 1 show that model No. 6 gives maximum value of positive bending moment (33630kN.m) and the maximum value of positive bending moment is 42204kN.m. within model No.7. For shear force, model No. 5 show the higher values of positive and negative shear force which is 12154kN and 11843kN respectively. Maximum tensile stress appears in model No.6 and No. 1(7.17MPa), thus these models will have more cracks. The maximum compressive stress is 10.98Mpa in model No.7. Model No.3 shows the maximum value of upward deflection which is 3mm and model No.5 gives maximum value of downward deflection (13mm). According to above results of pre-stressed load analysis for simply-supported tendons profile layout (case 1); model No.3 (straight tendon with three bends) is suitable for design because it shows upward vertical deflection more than others models. Models No.5 and No.6 are not suitable for design because of they appear maximum values of positive bending moment, shear force, and downward vertical deflection. Figure-2 shows the results of pre-stressed load stage fore case 1.



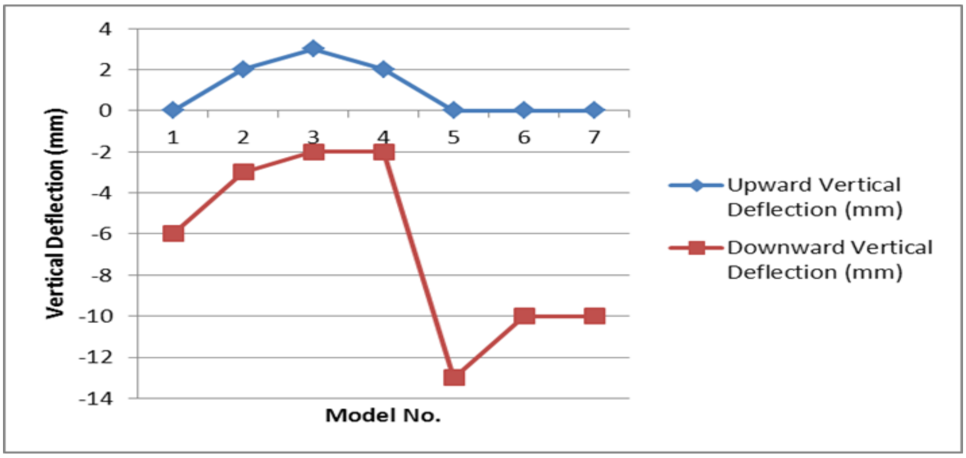
(a)



(b)



(c)



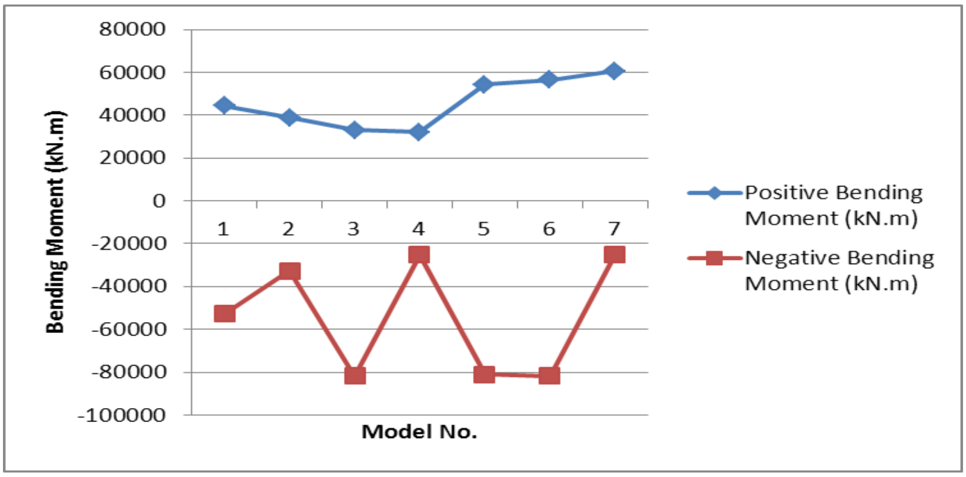
(d)

Figure-2. Results of pre-stressed load stage fore case 1: (a) bending moments, (b) shear forces, (c) stresses, (d) vertical deflection.

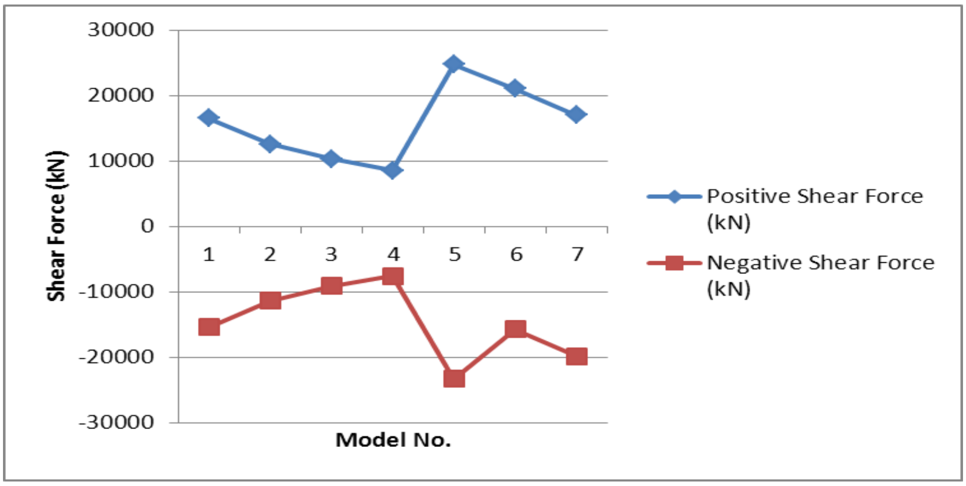
4.1.2 Service load stage

Figure-3 explains the results of service load stage analysis for case 1. From this Figure it can be seen that the minimum value of downward deflection is 15mm within model No. 3 and No.4, and maximum value is 27mm within model No.7. Model No. 6 gives the maximum value of compressive stress and model No. 7 shows maximum value of tensile stress. The higher value of positive and negative shear force is 24724kN and 23317kN within model No.5 respectively. Model No.7

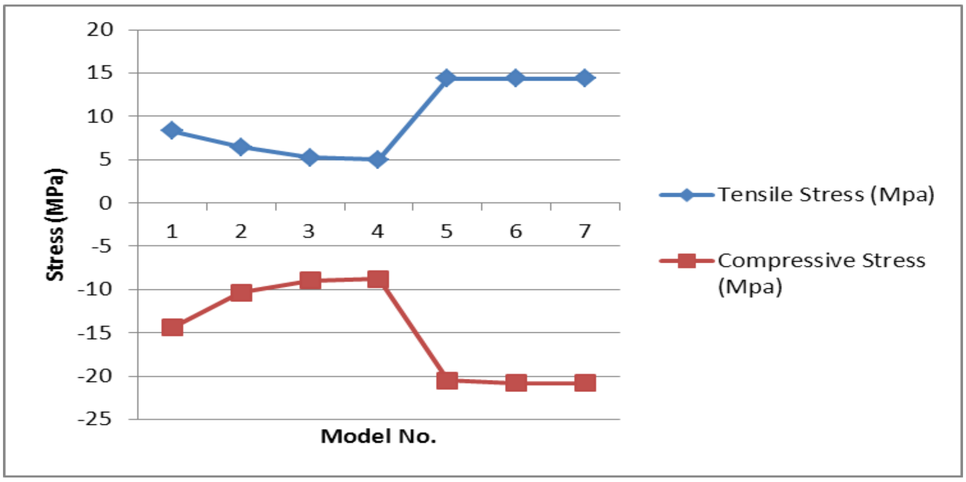
shows the maximum positive bending moment (60590kN.m) and Model No. 6 shows maximum negative bending moment (81892kN.m). From analysis, it can be concluded that model No. 3 (straight tendon with three bends) is more convenient from others models in the design of tendon profile layout.



(a)

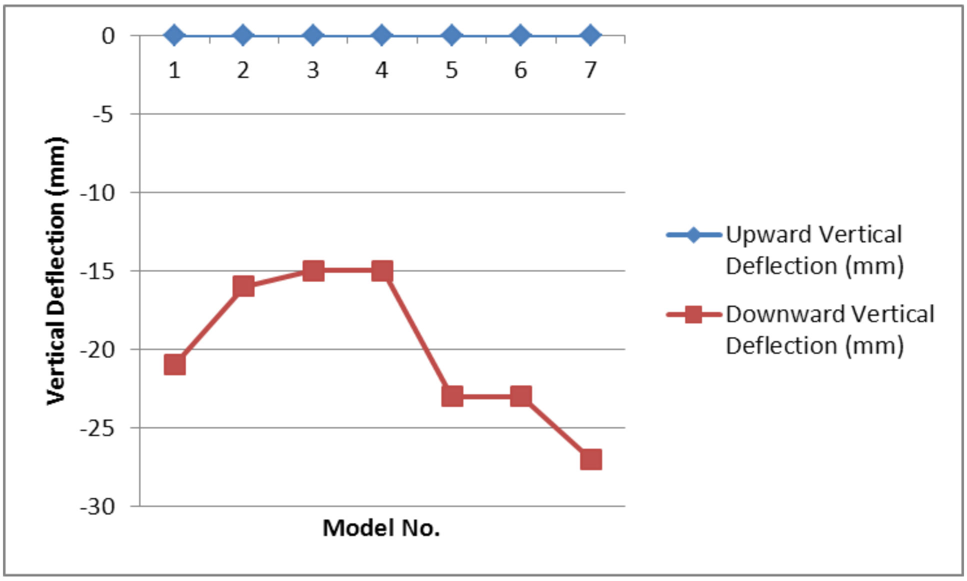


(b)



(c)

ARPN Journal of Engineering and Applied Sciences



(d)

Figure-3. Results of service load stage analysis for case 1: (a) bending moments, (b) shear forces, (c) stresses, (d) vertical deflection

4.2 FEM Analysis of continuous tendons profile layout (case 2)

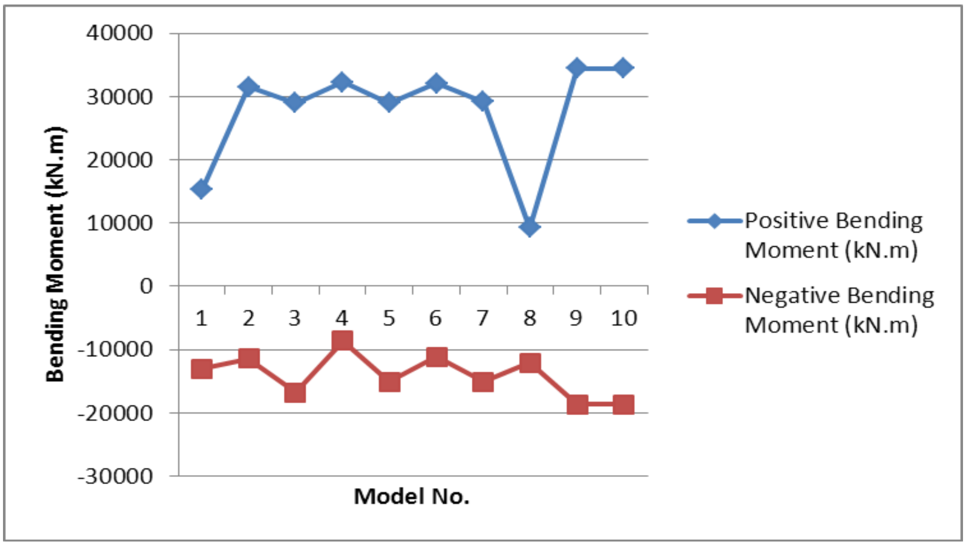
4.2.1 Pre-stressed load stage

The results of pre-stressed load stage can be seen that in Figure-4. This figure shows that the maximum upward vertical deflection appears in models No. 2, No. 4, No. 6 which is 2mm. These models also have smaller values of downward vertical deflection. Therefore, these models are more convenient to design of tendon profile layout according to vertical deflection evaluation because of the pre-stressed loads can be resisted the total loads of bridge structure. The maximum downward vertical deflection shows within model No. 10 and it is 12mm. indicating that pre-stressed load cannot carry the load of bridge structure. Model No. 8 gives the lower value of tensile stress (1.64MPa) and the higher value of tensile stress is 6.41MPa in model No.7. Therefore, the cracks will be appeared in this model. The maximum positive and negative shear force is 6642kN and 6637kN respectively within model No.6. Model No.10 shows the maximum positive bending moment (34393kN.m) and Model No. 9 shows maximum negative bending moment (18671kN.m).

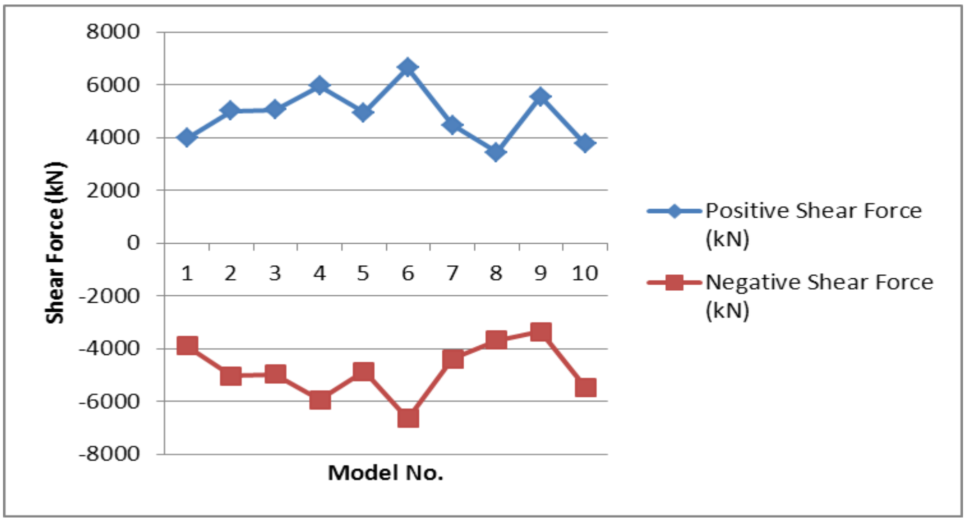
4.2.2 Service load stage

Service load stage represents the application of all loads (combinations of all types of loads) in the analysis of bridge structures models. The analysis results of this stage shows that the minimum value of downward vertical deflection is 14mm within models No. 4 and No.6. Therefore, these models have good opportunity to use in the design of tendon profile layout more than others models. Model No. 9 shows the maximum value of downward vertical deflection (26mm). The higher and lower values of tensile stress is 10.94MPa and 4.39MPa in model No. 9 and No.6 respectively. So model No. 9 will have more cracks than others models. For compressive stress, model No. 3 gives the maximum value which is 15.58MPa and the lower value is 8.85MPa in model No. 4. The maximum positive and negative shear force is 18116kN and 16929kN within model No.9 and No.8 respectively. The maximum positive and negative bending moment is 56444kN.m and 58376kN.m in model No.9. Figure-5 shows the analysis results of service load stage for case 2.

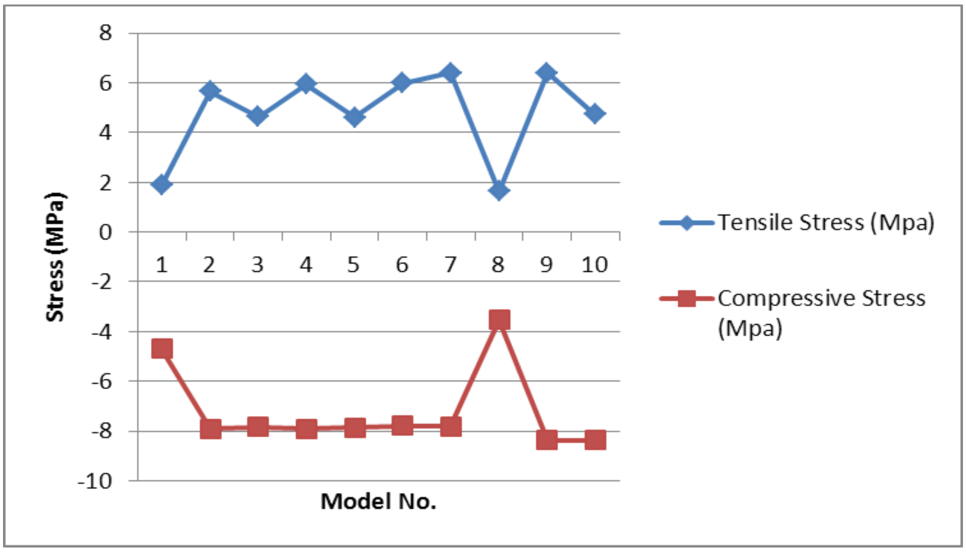
ARPN Journal of Engineering and Applied Sciences



(a)



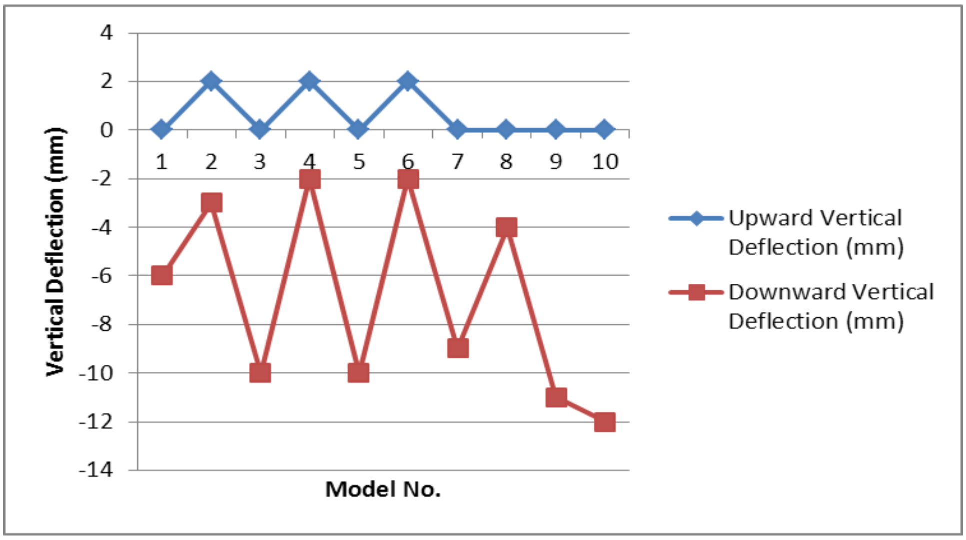
(b)



(c)

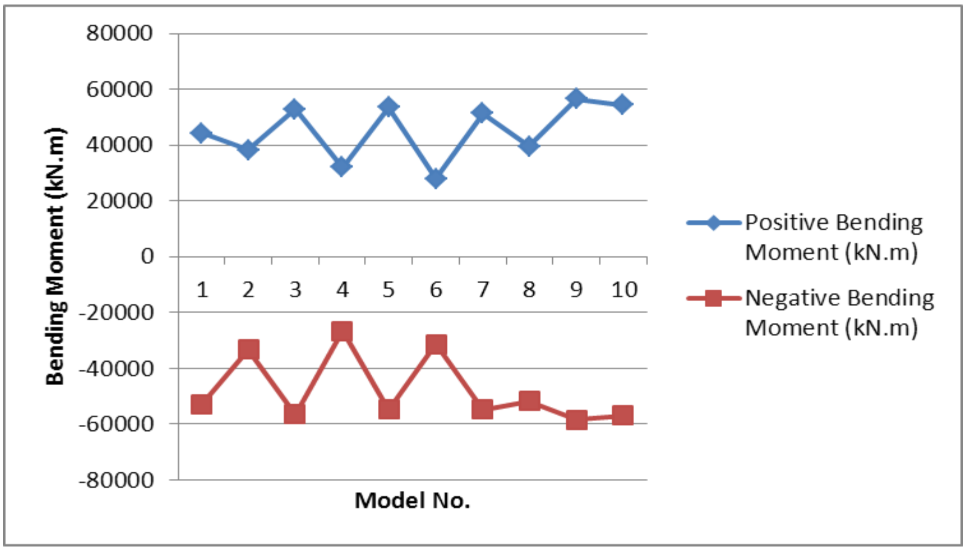
ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

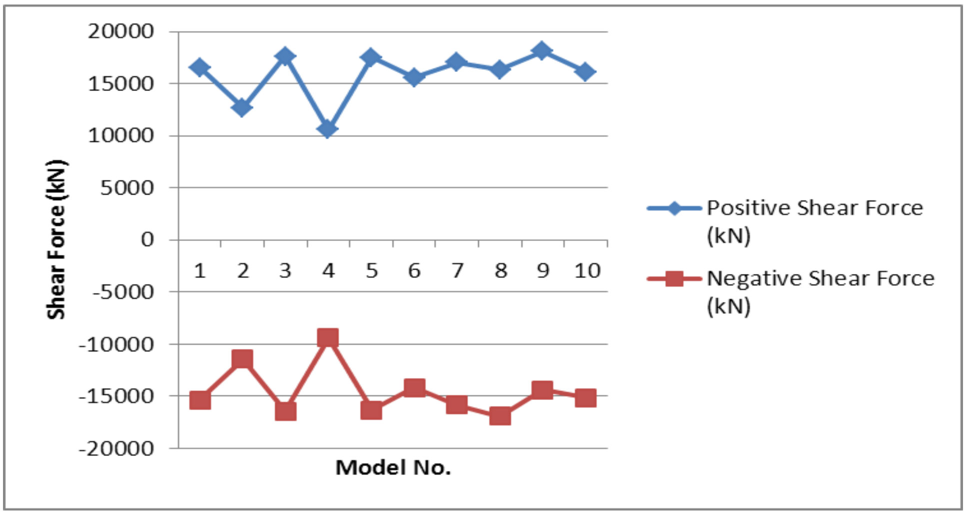


(d)

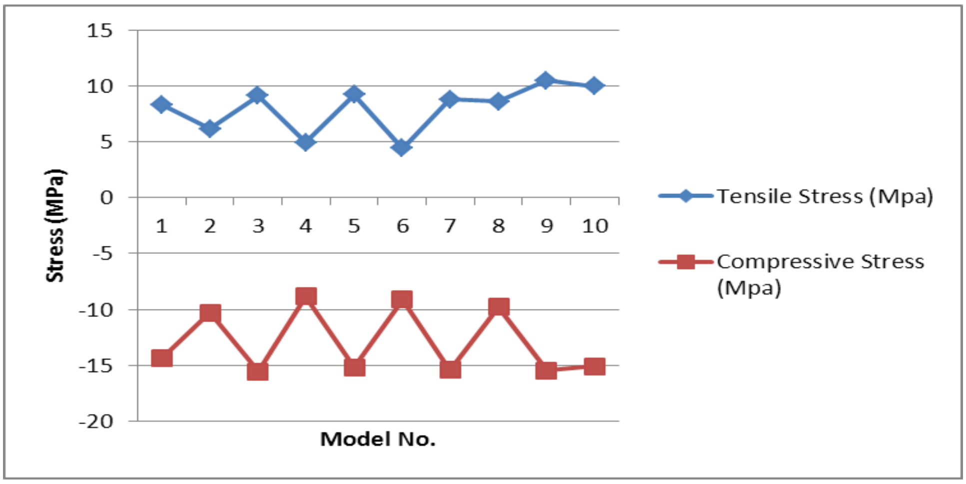
Figure-4. Analysis results of pre-stressed load stage for case 2: (a) bending moments, (b) shear forces, (c) stresses, (d) vertical deflection.



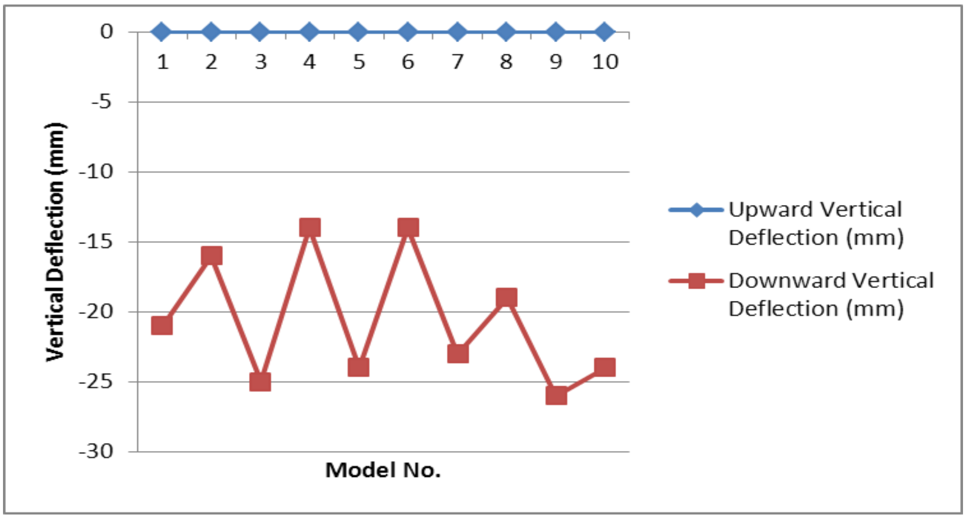
(a)



(b)



(c)



(d)

Figure-5. Analysis results of service load stage for case 2: (a) bending moments, (b) shear forces, (c) stresses, (d) vertical deflection.

5. COMPARISON OF PRE-STRESSED AND SERVICE LOAD STAGES

To compare between simply-supported and continuous tendon profile layout, upward and downward vertical deflection values are selected. For pre-stressed load stage, simply-supported tendon model appeared maximum value of upward vertical deflection (3mm) was more than continuous tendon model (2mm). The maximum downward vertical deflection is 12mm within continuous tendon model which is less than value of simply-supported tendon model (13mm). According to service load stage analysis, continuous tendon model had the minimum value of downward vertical deflection (14mm) was more than simply-supported tendon model (15mm), but maximum value of downward vertical deflection was appeared in simply-supported tendon model (27mm) was more than the maximum value of downward vertical deflection (26mm) within continuous tendon model. Figure-6 shows the comparison results for case 1. Figure-7 shows the comparison results for case 2.

VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

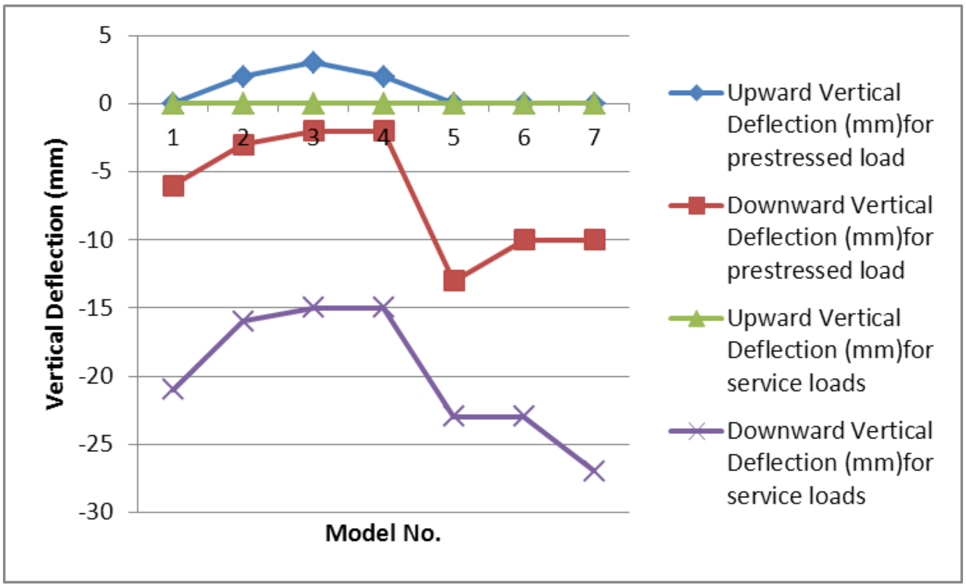


Figure-6. The comparison results for case 1.

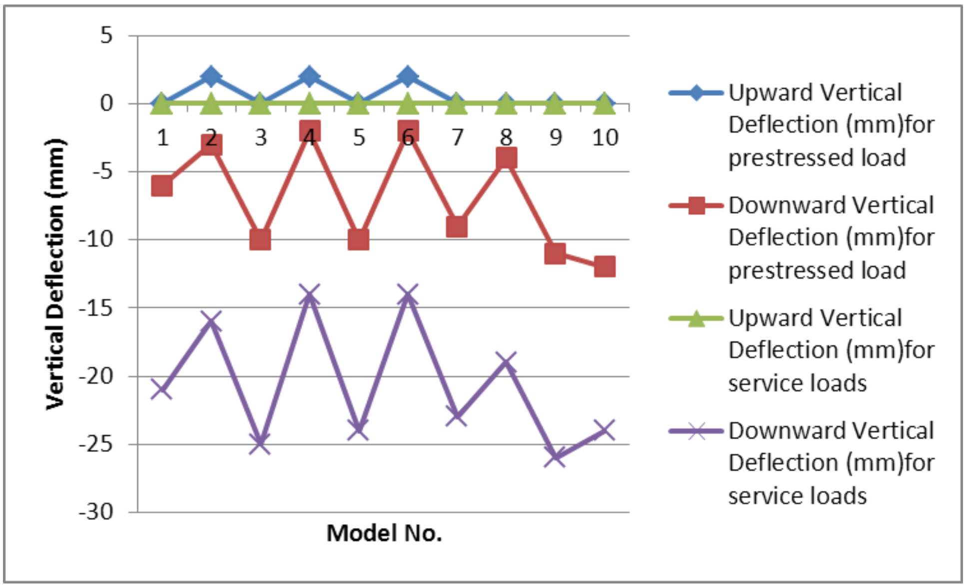


Figure-7. The comparison results for case 2.

6. CONCLUSIONS

a) Continuous box girder post-tensioned concrete bridge model is selected to evaluate the optimum design of tendon profile layout. According to supports of tendons anchorages, there are two cases of bridges models. The first case is used simply-supported tendons profile layout (the start anchorage and end anchorage of tendons along each span). The second case is adopted continuous tendons profile layout (the start anchorage and end anchorage of tendons along all spans). According to profile layout of tendons, the first case consists of seven bridge models (7-Models) and the second case includes ten bridge models (10-Models).

b) According to results of pre-stressed load stage analysis for simply-supported tendons profile layout (case 1), model No.3 (straight tendon with three bends) is suitable for design because it shows upward vertical deflection more than others models. Models No.5 and No.6 are not suitable for design because of they appear maximum values of positive bending moment, shear force, and downward vertical deflection. The minimum value of downward deflection is 15mm within model No. 3 and No.4, and maximum value is 27mm within model No.7. Therefore, it can be concluded that model No. 3 (straight tendon with three bends) is more convenient from others models in the design of tendon profile layout.

c) The results of pre-stressed load stage for continuous tendon profile model showed that the maximum upward vertical deflection appears in models No. 2, No. 4, No. 6 which is 2mm. These models also have smaller values of downward vertical deflection. Therefore, these models are more convenient to design of tendon profile layout according to vertical deflection evaluation because of the pre-stressed loads can be resisted the total loads of bridge structure. The maximum downward vertical deflection shows within model No. 10 and it is 12mm. indicating that pre-stressed load cannot carry the load of bridge structure. Model No. 7, No.6, No.9 give the higher value of tensile stress, the maximum positive and negative shear force, the maximum positive bending moment, and maximum negative bending moment respectively.

d) The analysis results of service load stages for continuous tendon profile model explained that the minimum value of downward vertical deflection is 14mm within models No. 4 and No.6. Therefore, these models have good opportunity to use in the design of tendon profile layout more than others models. Model No. 9 shows the maximum value of downward vertical deflection (26mm). The higher and lower value of tensile stress is appeared in model No. 9 and No.6 respectively.

For compressive stress, model No. 3 gives the maximum value which is 15.58MPa and the lower value is 8.85MPa in model No. 4. The maximum positive and negative shear force is 18116kN and 16929kN within model No.9 and No.8 respectively. The maximum positive and negative bending moment is 56444kN.m and 58376kN.m in model No.9.

REFERENCES

[1] A. S. Mohan. 2017. The Structural Behavior of Horizontally Curved Pre-stressed Concrete Box Girder Bridges, Thesis of the Doctor Degree of Philosophy, Submitted to School of Computing, Science and Engineering University of Salford, United Kingdom.

[2] A. F. Naser and W. Z. Lin. 2011. Experimental Inspection of Damage and Performance Evaluation after Repair and Strengthening of Jiamusi Highway Prestressed Concrete Bridge in China, World Academy of Science, Engineering and Technology. 73: 195-201.

[3] W. Al-Rifaie and A. Kareem. 1986. Bridges, first edition, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.

[4] Washington State Department of Transportation (WSDT). 2010. Washington State Bridge Inspection Manual, Technical Manual, Washington, USA.

[5] H. Arthur. 1987. Design of Pre-Stressed Concrete. Second Edition, Wiley, New York, USA. p. 592.

[6] A. F. Naser and W. Z. Lin. 2010. Strengthening of Jiamusi Pre-Stressed Concrete Highway Bridge by Using External Post-Tensioning Technology in China. ARPN Journal of Engineering and Applied Sciences. 5(11): 60-69.

[7] PCI. 1968. Fundamentals of Pre-Stressed Concrete Design. Second Edition. Pre-Stressed Concrete Institute, Chicago, USA.

[8] A. F. Naser and W. Z. Lin. 2013. Finite Element and Experimental Analysis and Evaluation of Static and Dynamic Responses of Oblique Pre-stressed Concrete Box Girder Bridge. Research Journal of Applied Sciences, Engineering and Technology. 6(19): 3642-3657.

[9] A. Abdullah, A. Jennifer, H. Hamilton, G. Consolazio. 2015. Damage Identification in Un-bonded Tendons for Post-tensioned Bridges. 6th International Conference on Advances in Experimental Structural Engineering, University of Illinois, Urbana-Champaign, USA.

[10] D. Trejo, M. Beth, P. G. Radhakrishna. 2009. Effect of Voids in Grouted, Post-Tensioned Concrete Bridge Construction, Report 0-4588-1 Vol. 1, Zachry Department of Civil Engineering and Texas Transportation Institute, USA.

[11] C. Cercone, C. Naito, J. Corven, S. Pessiki, W. Keller, S. Pakzad. 2015. Designing and Detailing Post Tensioned Bridges to Accommodate Non-Destructive Evaluation. Federal Highway Administration Project, ATLSS Report 14-01.

[12] J. Philippe, H. Rudolf, and P. Matt. 2005. Durability of Post-Tensioning Tendons, Technical Report, FIB Working Party 5.4.2, Durability Specifics for Pre-Stressed Concrete Structures.

[13] N. Fahmeen, V. Satheesh, M. Manigandan, S. Babu, 2015, An Overview on Tendon Layout for Pre-stressed Concrete Beams. International Journal of Innovative Science, Engineering and Technology. 2(9): 944-949.

[14] P. Ng and A. Kwan, 2006, Practical Determination of Pre-stress Tendon Profile by Load-balancing Method, TRANSACTIONS. 13(3): 27-35.

[15] A. Ali, K. Pathak, N. Dindorkar. 2010. Cable Layout Design of One Way Pre-stressed Concrete Slabs Using FEM. Journal of Engineering, science and Management Education. 2: 34-41.

[16] A. Ali, K. Pathak, N. Dindorkar. 2013. Cable Layout Design of Two Way pre-stressed Concrete Slabs Using FEM. Computers and Concrete. 11(1): 75-91.

[17] C. Kumar and L. Venkat. 2013. Genetic Algorithm Based Optimum Design of Pre-stressed Concrete Beam. International Journal of Civil and Structural Engineering. 3(3): 644-654.

[18] P. Colajania, A. Recuperob and N. Spinella. 2013. Design Procedure for Pre-stressed Concrete Beams. Journal of Computers and Concrete. 13(2): 235-253.

[19] A. Dixit and V. Khurd. 2017. Effect of Pre-stressing Force, Cable Profile and Eccentricity on Post Tensioned Beam. International Research Journal of Engineering and Technology. 4(11): 626-632.

[20] K. Abdul-Razzaq, A. Mohammed, T. Mohammedali. 2018. Finite Element Modeling of Post-Tensioned Two-Way Concrete Slabs under Flexural Loading. Civil Engineering Journal. 4(1): 1-10.