RESILIENT INFRASTRUCTURE
June 1–4, 2016

FINITE-ELEMENT MODELING FOR FRP STRENGTHENING OF PRESTRESSED CONCRETE BOX GIRDER BRIDGES BUILT BY CANTILEVER METHOD

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ABSTRACT

Balanced cantilever construction is an economical method when access from below is expensive or practically impossible. In segmental balanced cantilever construction the precast segments are transported to the bridge construction site and placed and held at the right position before post-tensioning back to the rest of the bridge. As the construction stages go on, the statically determinate structure changes to a statically indeterminate one, which should be considered in the design process. Creep and shrinkage of concrete and relaxation of prestressing steel may lead to excess long-term deflection and may cause redistributions in internal forces and stresses. In the previous study (Hedjazi et. al.) a general simulation for time-dependent analysis of segmentally erected prestressed concrete box-girder bridges has been presented. A three dimensional finite-element model for the balanced-cantilever construction of segmental bridges, including effects of the load history, material nonlinearity, creep, shrinkage, and aging of concrete and relaxation of prestressing steel was developed using ABAQUS software. The analysis has shown significant changes in the values of deflections, longitudinal stresses and internal forces as a result of long-term effects of creep and shrinkage of concrete and relaxation of the prestressing steel which has led to new arrangement and the increase in the number of mid-span continuity cables. But some times, adding new cables or rearranging the cables in existing bridges, is impossible. In these cases strengthening of the deck is a fast and economical solution. The aim of this study is to analyze the structural behavior of prestressed concrete box girder bridges when strengthening with fiber reinforced polymer laminates (FRP). Three examples of prestressed concrete box-girder bridges segmentally-erected using the balanced-cantilever technique have previously discussed to demonstrate their long-term behavior under dead load and effects of live load at the end of construction and different ages up to a thousand days by performing nonlinear analysis up to failure. In the present study, same examples of prestressed concrete box-girder bridges is being strengthened using FRP laminates. A moment–curvature analysis was subsequently carried out to investigate the flexural characteristics of the prestressed concrete box-girder bridges prior to and after strengthening with CFRP laminates. The results shows that significant strength can be gained at the ultimate limit state. The increase in flexural resistance at ultimate does provide an adequate margin of safety against further overloading.

Keywords: Segmental bridges; Box-girder; Prestress; Mid-span deflection; Strengthening with CFRP and GFRP laminates.

1. INTRODUCTION

The popularity of precast concrete segmental bridge construction has grown worldwide in the last few decades. These types of bridges offer many benefits to owners like reduced costs, reduced construction time, reduced environmental impacts, and reduced maintenance of traffic. These benefits can be achieved while utilizing local labor and materials, better means of quality control, and with minimum requirements for future maintenance. They also offer additional structural advantages of durability, fire resistance, deflection control, better rider serviceability, insensitivity to fatigue, and other redundancies. These bridges can accommodate highways, railways, and rapid transit, in both urban and rural environments. They can be straight or curved alignments, and can provide long spans for difficult obstructions and terrain. During construction stages and service life, time-dependent deformations of materials proved to have significant effects on the behavior of the bridge. Long-term deformations of material include those from creep and shrinkage of concrete and relaxation of prestressing steel. The time-dependent effects in the long term can cause poor ride quality, cracking, poor service and loss of durability in the bridge. Strengthening of prestressed concrete box girder bridges using fiber reinforced polymer (FRP) laminates is an easy and appropriate solution. Installation of this technique is relatively simple and can be achieved in a very short time. The system must be designed to avoid premature failure due to possible delamination or debonding of the CFRP material from the concrete surface. Alfred et al. in 2012 used models for fracture resistance of FRP sheets in strengthening prestressed concrete beams. The importance of the interaction between concrete and FRP and resin properties were emphasized, as the failure began in the interface between concrete and FRP. Rosenboom et al. in 2009 investigated the behavior of strengthened prestressed concrete beam in six specimens. They tested the specimens under static and fatigue loading conditions. The results indicated that the installation of a composite strengthening systems may result in increasing the cargo capacity of the samples, and in some cases, member's serviceability were increased.

Choo et al. in 2007 studied reinforced concrete bridges subjected to extreme loads and vehicles and examined the strengthening effects with FRP sheets. Analytical model indicated that considerable resistance can be obtained in the ultimate limit state and increase in ultimate flexural strength provides an adequate margin from safety against more overhead. Rizkalla and Hassan in 2002 worked on several large-scale models of prestressed concrete bridges to investigate failure and the effectiveness of different methods of strengthening with FRP. They achieved the desired result from increased resistance and reduced failure and deflection. Cost-effectiveness of methods to strengthen was considerable. In The North Carolina Department of Transportation (NCDOT), a research project with practical goals was initiated to evaluate the cost-effectiveness and value engineering of Carbon Fiber Reinforced Polymer (CFRP) repair and strengthening systems for prestressed concrete bridge girders. The experiments were under static loading conditions of eight prestressed concrete bridge girders, where six of them strengthened with various CFRP systems. Results show that the ultimate capacity of prestressed concrete bridge girders can be increased by as much as 73% using CFRP without sacrificing the ductility of the original member (Owen Rosenboom et al., 2007). Takacs and Kanstad showed that prestressed concrete girders could be strengthened with externally bonded CFRP to increase their ultimate flexural capacity. Two 11.3 m (37 ft) specimens plated with procured CFRP laminates achieved an increase in flexural moment capacity of 28% and 37%, respectively. Hassan and Rizkalla examined the flexural behavior of prestressed concrete bridge slabs strengthened with various CFRP systems. The flexural capacity of the slabs could be increased by as much as 50% using the CFRP strengthening, with the most cost effective solution being the CFRP sheets. A batch of constitutive models for prestressing tendon, concrete and fiber-reinforced plastic were proposed for the nonlinear finite element analysis of reinforced concrete structures strengthened by fiber-reinforced plastics and prestressed concrete structures strengthened by fiber-reinforced plastics. These material models have been tested against series of experimental data and good agreements have been obtained, which justifies the validity and the usefulness of the proposed nonlinear constitutive models (Hu et al., 2009).

Mayo et.al applied bonded FRP-laminates to strengthen and lift load restriction from a simple span, reinforced concrete slab bridge in Missouri. Behavior of reinforced-concrete beams strengthened with bonded CFRP-plates was investigated by Spadea et.al. Their study emphasized importance of consideration of end-anchorage stresses in the design and indicated as much as 70% increase in load capacity when external anchorages are used. Hag-Elsafi et al. investigated load testing for evaluating effectiveness of FRP composites in reinforced concrete bridge rehabilitation. Hag-Elsafi et al. discussed application of FRP materials in retrofitting reinforced-concrete bridge members. Hag-Elsafi and Alampalli investigated similar applications for prestressed concrete bridge members. Anchorage stresses and bond between the laminates and concrete were studied by various researchers, including Mukhopadhyaya and Swamy, Neubaurer and Rostasy, Ueda et al., Brosens and Van Gemert, and Rabinovitch and Frostig. Some of these efforts resulted in development of equations to estimate anchorage length, and all emphasized the importance of proper anchorage and consideration of laminate bond in design. Fatigue strength of concrete beams (reinforced and non-reinforced) strengthened by externally bonded CFRP laminates was studied by Muszynski and Sierakowski. The bonded FRP laminates were used by the New York State Department of Transportation in a demonstration project to repair girders of a concrete T-beam bridge to increase their flexural and shear capacities. The bridge was instrumented and load tested twice before and after the installation of the FRP laminate system (Osman Hag-Elsafi et al., 2001).

This paper is intended to provide bridge engineers and researchers with data for better understanding of the strengthening of prestressed concrete box girder bridges using fiber reinforced polymer (FRP) laminates. The finite-element computer program "ABAQUS" is used to simulate the time-dependent effects due to creep and shrinkage of concrete, relaxation of prestressing steel, changing of concrete properties with time, and strengthening using FRP laminates and also to investigate changes in the flexural capacity of the models retrofitted with FRP laminates.

2. DESCRIPTION OF THE FINITE-ELEMENT MODEL

The general purpose finite-element "ABAQUS" software is used for the numerical simulation of three segmental bridges built by balanced cantilever construction method and then strengthened with fiber reinforced polymer (FRP) laminates. The models in this study, are including three types of materials with specific properties. These materials include reinforced concrete, prestressing cables and composite plates. Concrete is defined of elements, C3D8R (eight-node solid elements with reduced integration) and C3D4 (four-node solid elements), and to simulate the linear and nonlinear behavior of concrete, the User's Option of Material Property is used, in which the compressive stresses, tensile and plastic strain are identified by the user. The characteristics of reinforcement separately defined in the material property section. To do so it is necessary to define stress-strain curve of steel in Abaqus. The stress-strain curve of concrete were determined using Hagnstad relations with the final strain assumption of about 0.003. Modulus of elasticity, Ec(t) can be calculated as follows:

$$E_c = 0.043 w_c^{1.5} \sqrt{f_c'} \quad [1]$$

w_c and f_c' are unit weight of concrete and compressive strength of concrete at 28 days respectively (ACI Committee 209, 1992). The interaction between concrete and tendons was defined using the Optional Module of Interaction as Embedded Region. For modeling of the prestressed cables the element T3D2 is used, which is a two-node truss element. Element type S4R is used to model the composite plates. In this paper three examples of multi-span bridge built by cantilever technique (Ketchum and Scordelis 1986; Chiu et al. 1996; Hedjazi et al. 2007) are assumed and after strengthening with fiber reinforced polymer (FRP) laminates analyzed using ABAQUS software. Length of the spans of the samples, include 76.2 m(MSB1), 150 m(EX1) and 200 m(EX2) and each span consists of twenty, Forty and Fifty-two precast segments, respectively. More details about these examples can be found elsewhere (Ketchum and Scordelis 1986; Chiu et al. 1996).

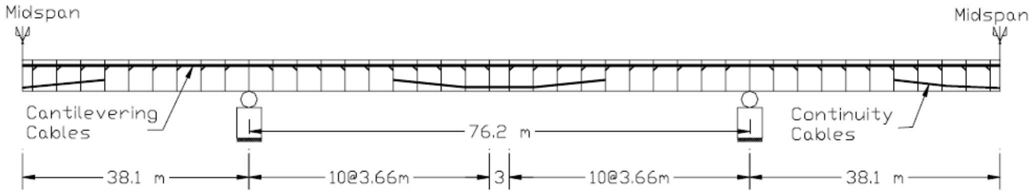


Figure 1: Layout of segments and cantilever tendons and continuity cables (MSB1)

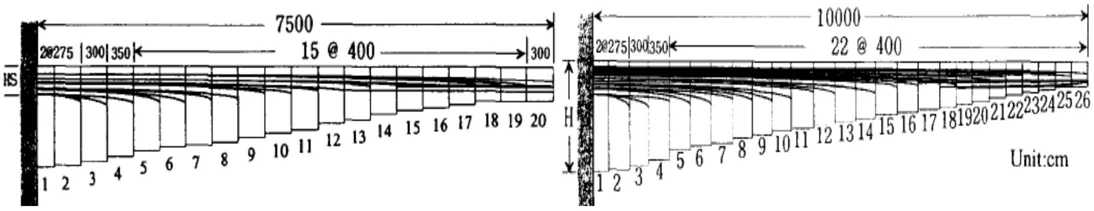


Figure 2: Layout of segments and cantilever tendons (EX1, EX2)

3. DISCUSSIONS OF THE RESULTS

To examine the accuracy of time-dependent analysis and simulation of strengthening of prestressed concrete beams, an experimental work on simple support beams conducted at Taiwan University (Chiu et al. 1996) is selected (Hedjazi et al. 2007). These tests were performed on six laboratory-scale prestressed concrete beams to investigate their behavior under the effects of long-term deformation of materials and to verify a control method finite-element approach for segmental bridges built by the balanced cantilever method. Figure 3 shows the test set up and beam dimensioning. More details can found elsewhere (Chiu et al. 1996). Beam elements with prestressing cables are used to model the tested beams and then modeled by solid elements strengthened with CFRP Laminates. Comparison between the analytical results and experimental findings with and without CFRP Laminates is shown in Figure 4. The analysis results show that the beams strengthened with CFRP have reduction in mid-span deflection and their bearing capacity have increased up to 34.7 percent which was expected.

After verifying the changes of bending capacity, finite-element computer modeling is constructed, using ABAQUS software. The bridges prototype shown earlier in this paper is modeled using the balanced cantilever erection technique. View of the finite-element models of the segmental bridges considered herein is shown in Figure 5 and Figure 6. After modeling, simulation and verification, the bridges were simulated using various layers of FRP sheet. Characteristics of CFRP, GFRP fibers used in this analysis and the graph obtained from the analysis of strengthened bridges, are shown in Table (1), (2) and Figures 7 and 8, respectively.

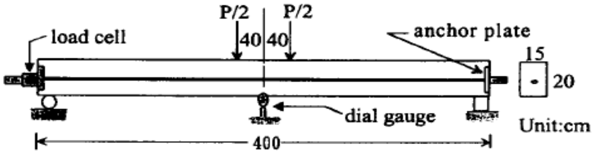


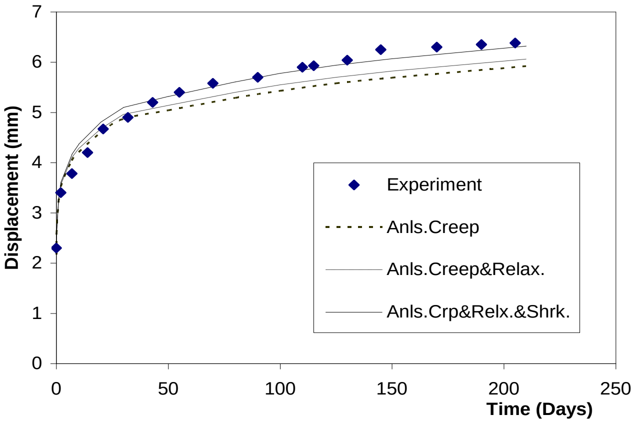
Figure 3: Flexural test set up (quoted from Chiu et al. 1996)

Table 1: Characteristics of CFRP fibers

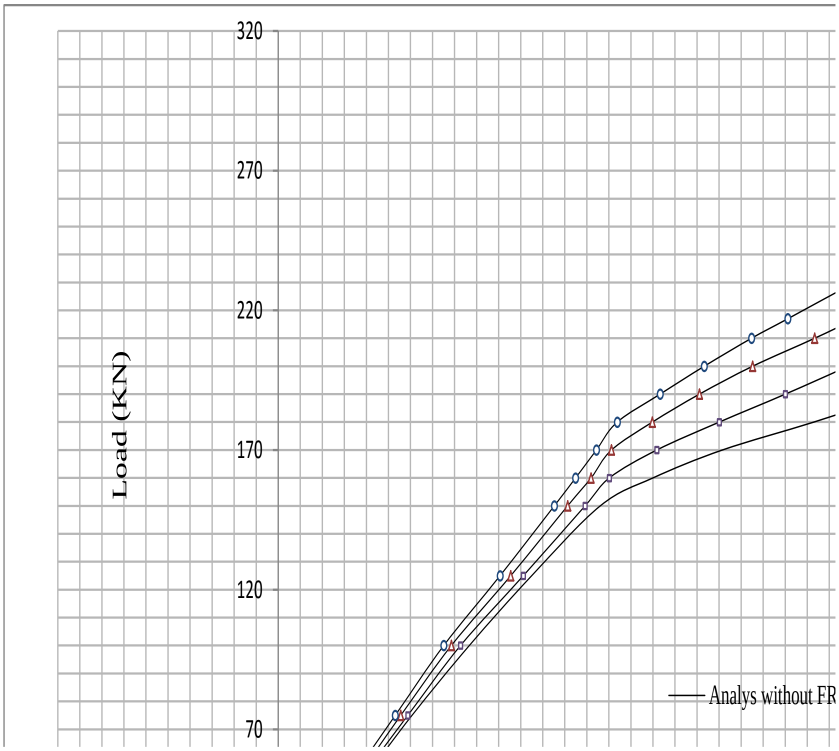
Tensile Strength (MPa)	Tensile modulus (MPa)	Ultimate Elongation	Density (kg/m^3)	Weight per square meter (kg/m^2)	Thickness (mm)
3790	230,000	0.017	1740	0.664	1.0

Table 2: Characteristics of GFRP fibers

Tensile Strength (MPa)	Tensile modulus (MPa)	Thickness (mm)	Thickness (fibers) mm	Density (kg/m^3)
3400	73,000	1.0	0.363	2600



a) Comparison between experimental and analytical results: Deflection at beam mid-span versus time



b) Mid-span Deflection of beam with and without CFRP Laminates

Figure 4: Mid-span Deflection

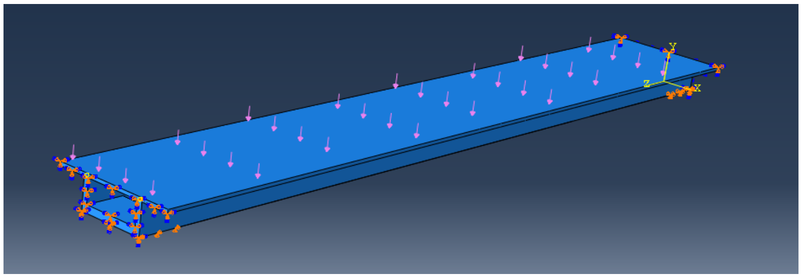


Figure 5: Bridge view of the finite-element model (MSB1)

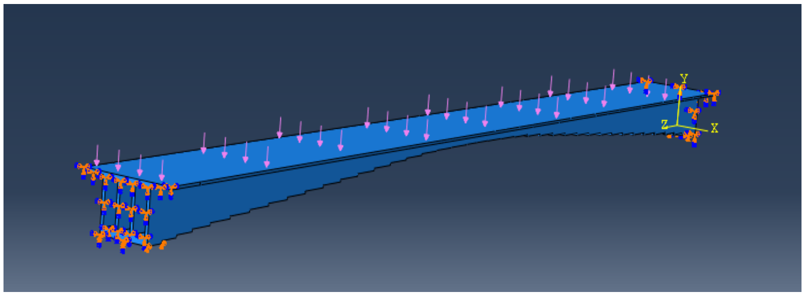


Figure 6: Bridge view of the finite-element model (EX1, EX2)

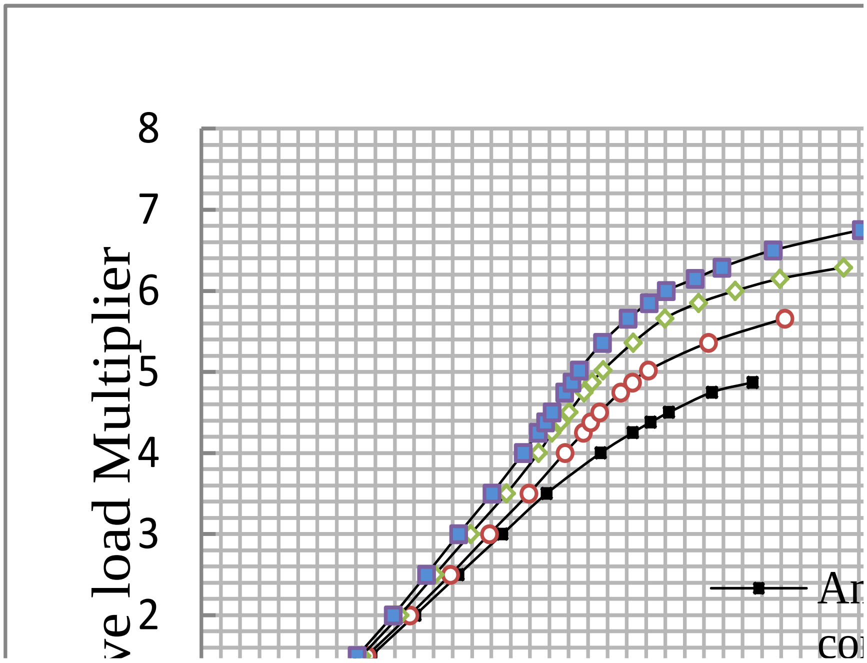


Figure 7: Mid-span deflection diagram of bridge MSB1 at the end of construction

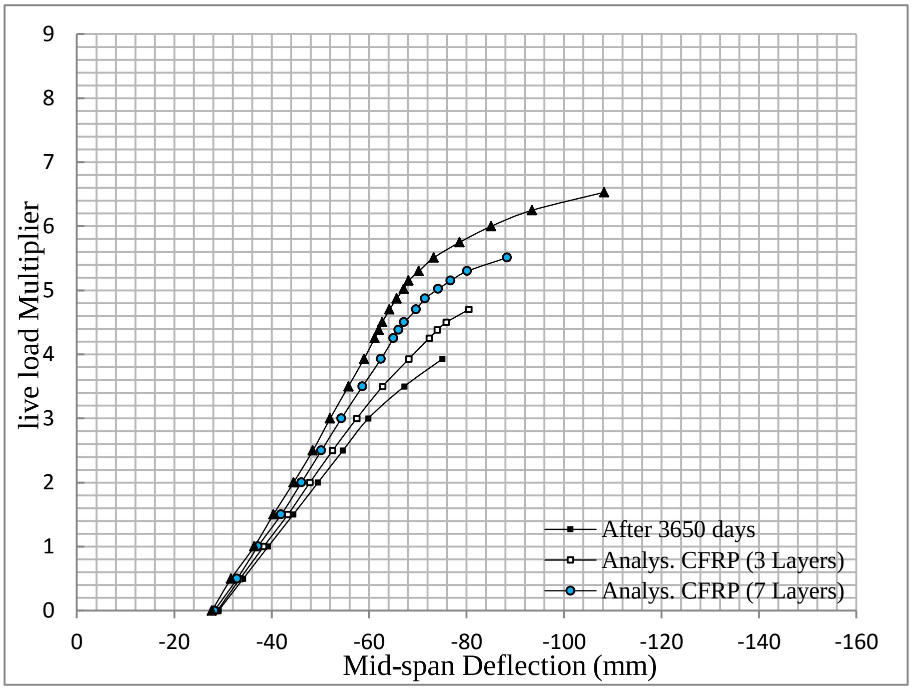


Figure 8: Mid-span deflection diagram of bridge MSB1 after 10 years after construction

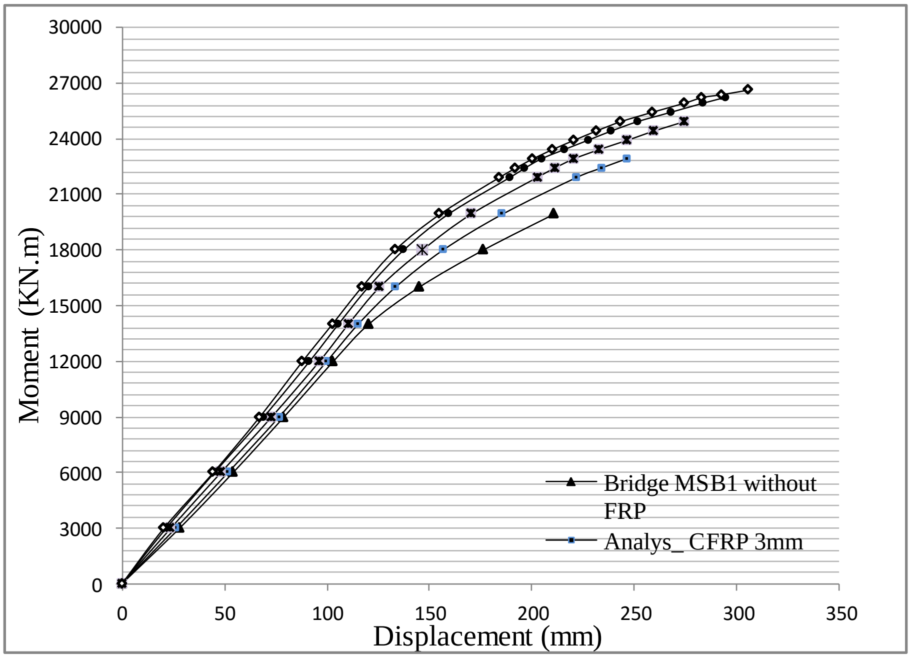


Figure 9: Mid-span moment-deformation diagram of bridge MSB1 with various layers of CFRP

As shown in Figures 7 and 8, MSB1 bridge's bearing capacity after strengthening with CFRP Laminates has increased significantly. In addition, the deformation of the mid-span of the bridge reduced according to the number of CFRP layers. According to Figure 9, it is shown that the moment capacity of the bridge after strengthening with CFRP Laminates can increase up to 25.16 percent. Strengthening the bridge within the range of 9 to 12 layers of FRP sheets shows little effect on flexural capacity of the bridge, and that expresses after certain point the number of layers has not significant effect on the bridge flexural capacity as the failure mode has changed.

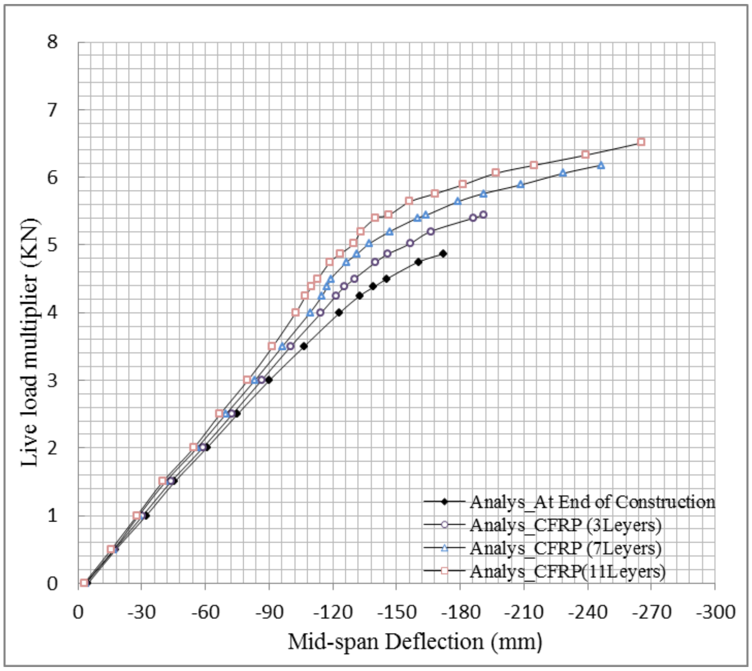


Figure 10: Mid-span deflection diagram bridge EX1 at the end of construction

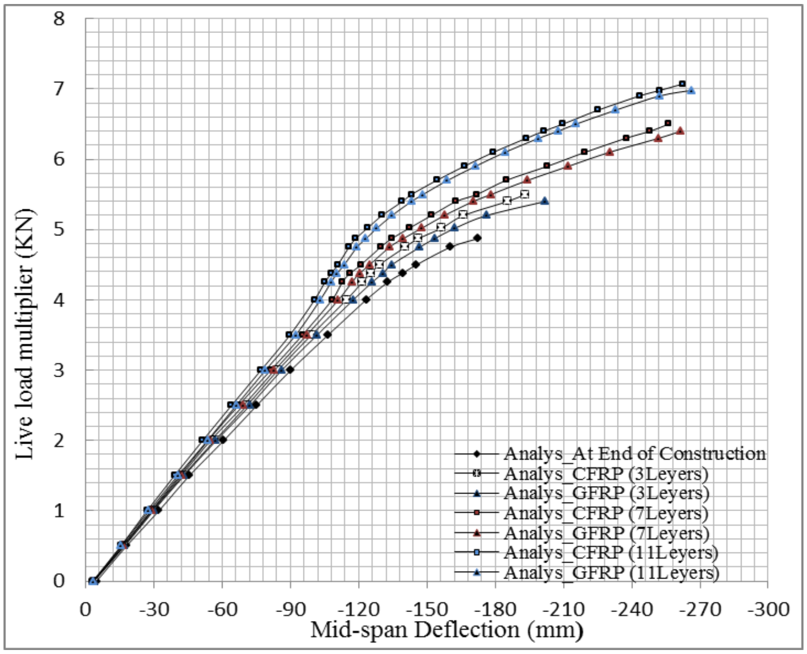


Figure 11: Mid-span deflection diagram of bridge EX1 at the end of construction

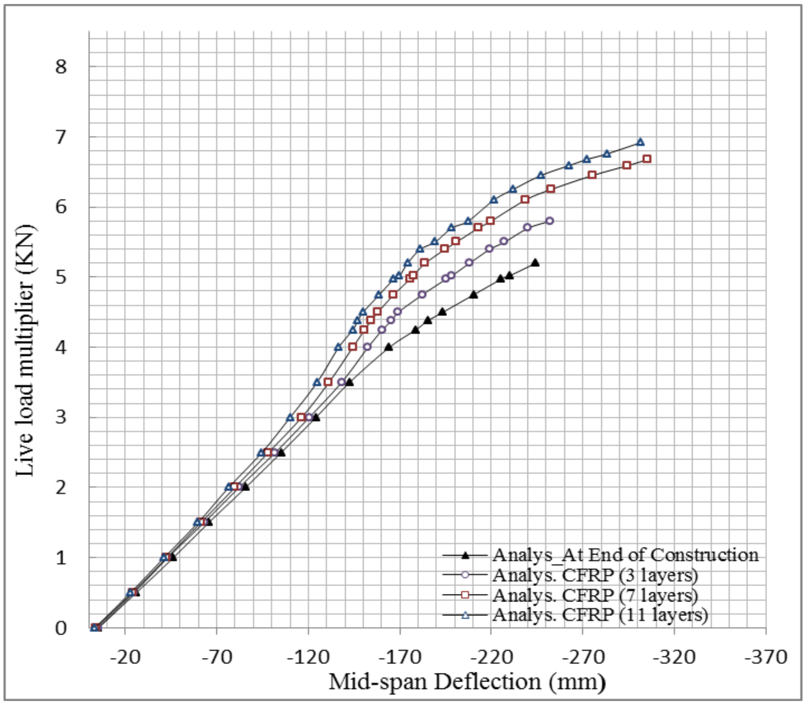


Figure 12: Mid-span deflection diagram of bridge EX2 at the end of construction

Figure 10, 12 shows that the retrofit of bridges with CFRP laminates will have a significant impact on increasing the ultimate load bearing capacity up to 31.12, 33.46 percent, respectively. The analysis results in Figure 11,13 show that the percent of increase in the load bearing capacity of the bridge strengthened using CFRP layers is greater than using GFRP sheets but strengthening with GFRP sheets compared with CFRP sheets shows more flexibility.

Table 3: Percent of increase in flexural capacity of the bridge MSB1 using layers of CFRP

Layers of CFRP (mm)	Percent of increase in load bearing capacity %	Layers of CFRP (mm)	Percent of increase in flexural capacity
3	13.95	3	13.08
7	22.57	6	20.10
10	31.88	9	24.02
-	-	12	25.16

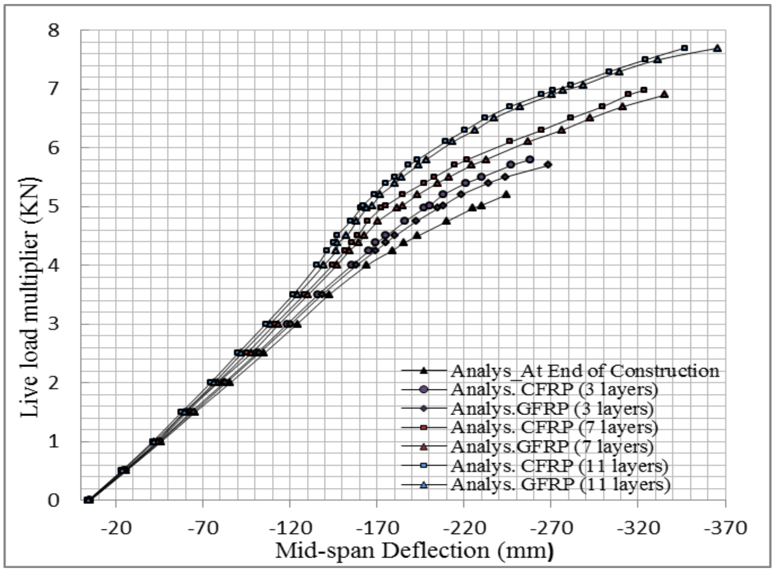


Figure 13: Mid-span deflection diagram of bridge EX2 at the end of construction

4. CONCULUSIONS

A general method for simulating of construction and strengthening analysis of with FRP laminates for segmental prestressed concrete bridges built by balanced-cantilever method is proposed. Loads are gradually applied to the structures, in the construction phase and after that up to 10 years. Time dependent effects including creep, and shrinkage of concrete and relaxation of cables have been considered in the long term analysis. In this study, three bridges, MSB1, EX1 and EX2 modeled and then after strengthening using the various layers GFRP and CFRP, the effect of the number of layers on reducing mid-span deflection and increasing load bearing capacity have been investigated. Changes in flexural behavior and capacity of bridges after strengthening with different layers of FRP investigated and showed limited increase. It is shown that increasing the number of layers of FRP sheets has limited effect on the flexural capacity as the failure mode may change. The analysis show that strengthening of studied prestressed box bridges using CFRP and GFRP sheets, can result in more load bearing capacity of the bridges strengthened with CFRP plates and better flexibility of the bridges strengthened with GFRP sheets. The comparisons between ABAQUS predictions and the experimental data show that the proposed FE models are good representations for both time effects and immediate load effects. Generally, modeling a reinforced concrete structure in a nonlinear analysis in ABAQUS is very sensitive to changes in material properties and can be affected due to different parameters such as mesh size and load steps.

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