Performance and Reliability of Bridge Girders Upgraded with Post-tensioned Near-surface-mounted Composite Strips

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Abstract: This paper deals with a research program concerning the performance and reliability of bridge girders strengthened with post-tensioned near-surface mounted (NSM) carbon fiber reinforced polymer (CFRP) composite strips. The advantages of CFRP application include non-corrosive characteristics, prompt execution on site, reduced maintenance expenses, favorable strength-to-weight ratio, and good chemical or fatigue resistance. NSM CFRP technologies are emerging in the infrastructure rehabilitation community because of several benefits such as enhanced bond performance and durability. For the present study, computational and analytical approaches are employed to examine the behavior of CFRP-strengthened girders, including 51 finite element models. Preliminary reliability analysis is conducted for evaluating the level of safety associated with the strengthened girders.

Keywords: bridge, composite, performance, rehabilitation

1. INTRODUCTION

Constructed bridge structures require significant attention due to the degradation of constituent members. Typical attributes causing structural deterioration include increased service load and environmental distress. Carbon fiber reinforced polymer (CFRP) composites have demonstrated promising performance in terms of upgrading the behavior of existing structural members [1]. Two types of CFRP application may be used for practice:

- Externally bonded (EB) CFRP: CFRP sheets/laminates are bonded to the substrate of the structural element using an adhesive
- Near-surface mounted (NSM) CFRP: CFRP strips/rods are inserted into precut slits along the member and bonded permanently

The EB method has been used since the late 1990s, while the NSM method has relatively short history [2]. The former is usually susceptible to premature CFRP-debonding, whereas the latter shows enhanced bond resistance. Additional benefits of using NSM CFRP are prompt installation with reduced labor, enhanced durability, and satisfactory aesthetics [3-5]. Prestress may be applied to augment the efficacy of NSM CFRP. The reason is that only a certain range of CFRP strength can be used when the strengthened structure fails, provided the capacity of CFRP materials is substantially high [6]. Several prestressing methods (i.e., post-tensioning hereafter) have been proposed previously such as external jacking device [7,8], brackets [9], and embedded anchors [10]. Research projects have been reported in the area of post-tensioned NSM CFRP for upgrading concrete members. Nordin and Taljsten [11] reported test results concerning the behavior of reinforced concrete beams retrofitted with post-tensioned NSM CFRP that was tensioned using external jacking device. The strengthened beams revealed improved cracking and yield capacities in comparison to an unstrengthened control. Badawi and Soudki [12] predicted the flexure of reinforced concrete beams upgraded with post-tensioned NSM CFRP. Sectional analysis was employed based on force equilibrium, material nonlinearity, and strain compatibility. Although the capacities of the strengthened beams increased

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(i.e., yield and ultimate loads), ductility of these beams decreased with an increasing level of post-tensioning. Choi et al. [8] tested reinforced concrete T-beams retrofitted with post-tensioned NSM CFRP. The beams had partial CFRP-bonding induced by use of a thin plastic duct (i.e., 0.4L to 0.75L in which L is the beam span). Various levels of post-tensioning were applied from 40% to 60% of the CFRP capacity. Enhanced deformability was noticed because of the partial bonding scheme and this effect became more obvious when a post-tension force increased. El-Hacha and Gaafar [9] compared the behavior of concrete beams strengthened with NSM CFRP with and without post-tensioning. The beam with post-tensioning demonstrated better serviceability such as lower deflection when compared with the beam without post-tensioning. It was also noted that the loss of post-tension force was not significant. Wahab et al. [13] reported the fatigue response of reinforced concrete beams post-tensioned with NSM CFRP. The fatigue range implemented was up to 70% of the control capacity. CFRP-slip was observed while the beam was submitted to fatigue cycles. Failure of the fatigue beams was resulted from CFRP-debonding and steel rupture. The surface condition of the CFRP affected the performance of the test beams such that sand-coated CFRP showed longer fatigue life than spirally wound CFRP did.

As discussed above, post-tensioned NSM CFRP is a promising technique that can improve the behavior of existing concrete members. It is, however, important to note that this emerging strengthening method is still in an early stage and further development is necessary. This paper deals with a numerical approach predicting the behavior of prestressed concrete bridge girders strengthened using post-tensioned NSM CFRP. A three-dimensional finite element model was developed to examine the flexure of the strengthened girders. An analytical approach (i.e., strain compatibility) was employed to estimate the capacity of the girders. A preliminary reliability study was reported.

2. RESEARCH SIGNIFICANCE

Effort is required to better understand the behavior of existing concrete members when upgraded with post-tensioned NSM CFRP. The current state of research remains in laboratory-scale investigations. Limited endeavors have been made in terms of design guidelines that can lead to the full-scale site application of this technology. For example, the effect of CFRP-bonded length and post-tensioning levels that will influence the performance of strengthened members is not known. The reliability of the girders strengthened with post-tensioned NSM CFRP is also of interest from a practice point of view. The research program addresses these technical challenges associated with post-tensioned NSM CFRP technologies.

3. PROTOTYPE BRIDGE GIRDERS AND STRENGTHENING SCHEMES

This section explains the background of the numerical study conducted to examine the behavior of bridge girders upgraded with post-tensioned NSM CFRP strips. Below is a summary of material properties, girder details, and strengthening schemes.

3.1. Materials

The specified 28-day compressive strength of concrete was 40 MPa and its elastic modulus was 30 GPa with a Poisson's ratio of 0.2. The ultimate strength of 7-wire prestressing steel strands was 1860 MPa with a modulus of 190 GPa and a Poisson's ratio of 0.3. The unidirectional CFRP used included the following material properties [14]: ultimate tensile strength = 2500 MPa, modulus = 165 GPa, rupture strain = 1.48%, and Poisson's ratio = 0.25. The level of post-tensioning force was up to 981 kN to upgrade the performance of constructed bridges (details follow) according to a preliminary study: a cross sectional area of 700 mm^2 was required for the NSM CFRP to satisfy the provision of the ACI.440.4R-04 document [15].

3.2. Details of Prototype Girders

Prototype girders were taken from the standard girders used in Korea. Three types of girders were used in this research program (L = 25, 30, and 35 m), as shown in Fig. 1. Three to five bundled strands were draped along the girder span and their cross-sectional areas were 3560 mm^2, 4750 mm^2, and 5940 mm^2 with prestressing levels of 64%, 65%, and 68% as per the Korean Standard [16] for the girders with L = 25, 30, and 35 m, respectively.

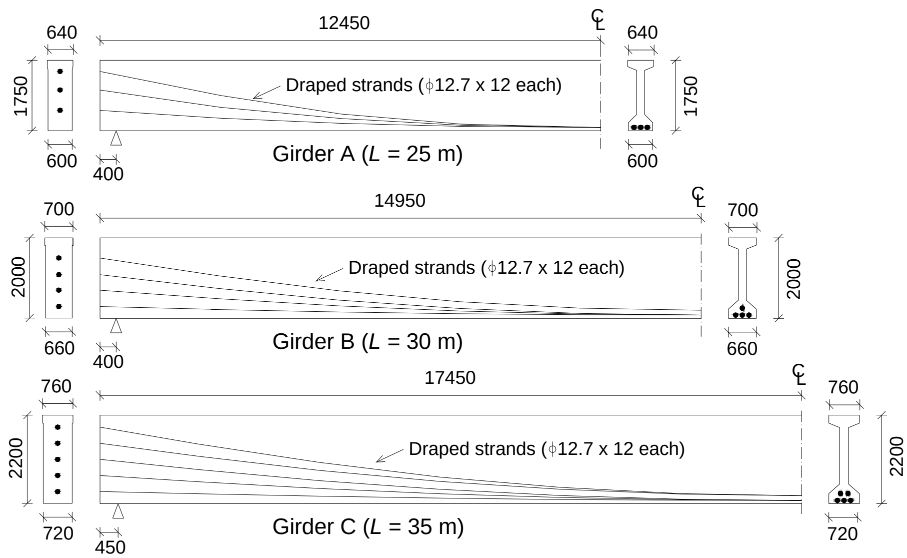


Figure 1: Prototype bridge girders

3.3. Strengthening Plan

The following was intended to strengthen the prototype girders shown in Fig. 1: a girder carrying a design load of 318 kN (designated DB-18 in Korean Standard) is upgraded to the girder resisting a load of 424 kN (DB-24). The details of DB-24 truck load are provided in Fig. 2.

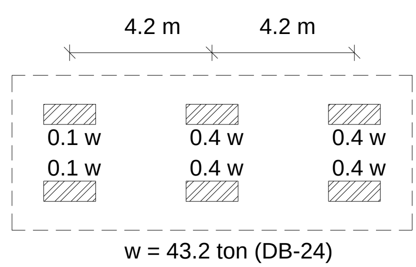


Figure 2: Design live load DB-24

Figure 3 shows the proposed strengthening plan based on the patented technology. The sequences of implementing this method are as follows:

(a) *Cutting a groove*: a narrow groove is cut for inserting NSM CFRP along the girder span. Additional space is required for mounting anchorage at both ends of the groove.
(b) *Installing anchorage*: anchor bearing blocks are positioned inside the precut anchorage space and fixed with anchor bolts.
(c) *Installing jacking apparatus*: NSM CFRP is located along the groove and connected with jacking apparatus for post-tensioning.

(d) *Jacking operation*: a hydraulic jack is placed within the jacking apparatus and a pressure is applied to the system until a desired post-tensioning force is achieved.
(e) *Transferring post-tension force*: once the post-tensioning force is achieved, the jacking apparatus is removed and the force is transferred to the bearing-anchor blocks.
(f) *Grouting*: all the precut regions are grouted with a cementitious material to improve the aesthetics of the strengthened member.

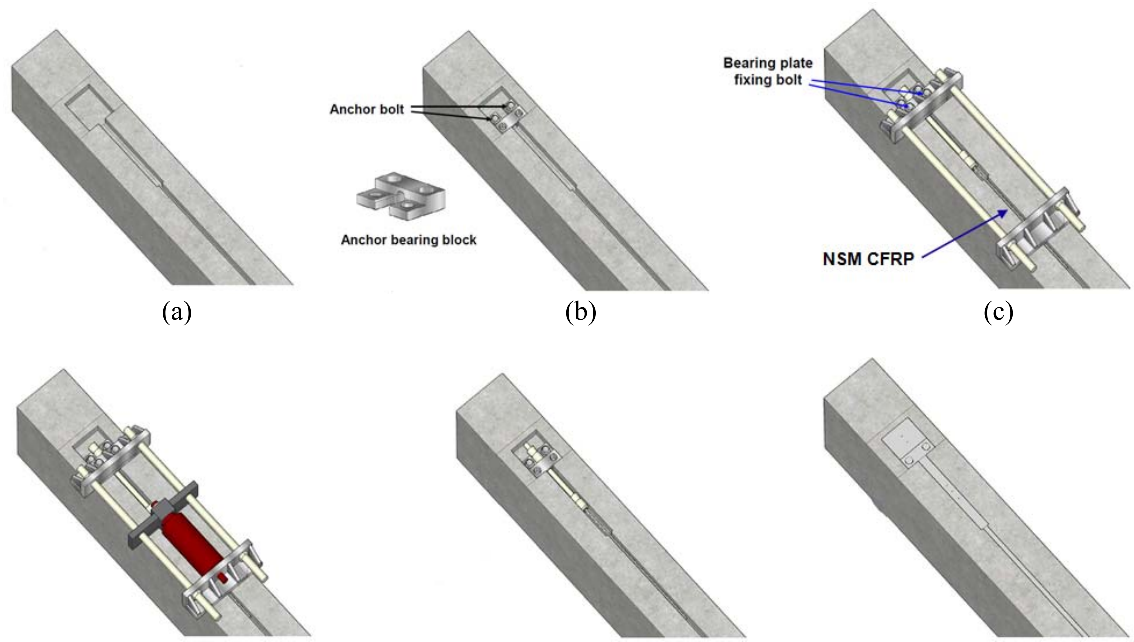


Figure 3: Proposed strengthening plan (patent numbers 10-0653632, 10-1005347, and 10-1083626): (a) cutting a groove; (b) installing anchorage; (c) installing jacking apparatus; (d) jacking operation; (e) transferring post-tension force; (f) grouting

To examine the effect of post-tensioning, various forces were planned from 0%f_{fu} to 60%f_{fu}, where f_{fu} is the ultimate capacity of the CFRP, which were equivalent to post-tensioning forces from 0 kN to 981 kN. An expression was proposed to assist examining the effectiveness of the NSM CFRP for upgrading an existing bridge girder: $\alpha = L_p/L$ where α is the strengthening coefficient and L_p is the bond length of the NSM CFRP.

4. RESEARCH APPROACH

The research approach taken was two-fold: i) three-dimensional finite element analysis for global response investigations and ii) a preliminary reliability examination.

4.1. Finite Element Modeling

The commercial finite element package ANSYS was used. Figure 4 shows a constructed model with elements. Four-node elastic shell elements were used to represent the girder concrete. This element has six degrees of freedom at each node (i.e., three rotational and three translational degrees of freedom). Three-dimensional link elements were employed for modeling the prestressing strands and the CFRP, which would show unidirectional behavior in tension and compression. To facilitate computational modeling, the multiple prestressing strands shown in Fig. 1 were simplified to one representative tendon with the same center of gravity (Fig. 4). A function called INISTATE was used to apply a prestressing force to the steel and the CFRP: the link element was subjected to an initial strain equivalent to the desired prestressing force levels explained earlier.

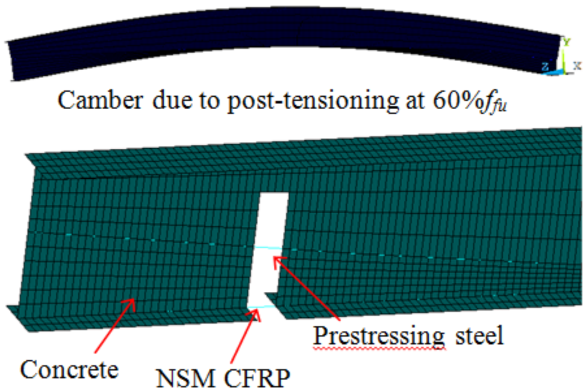
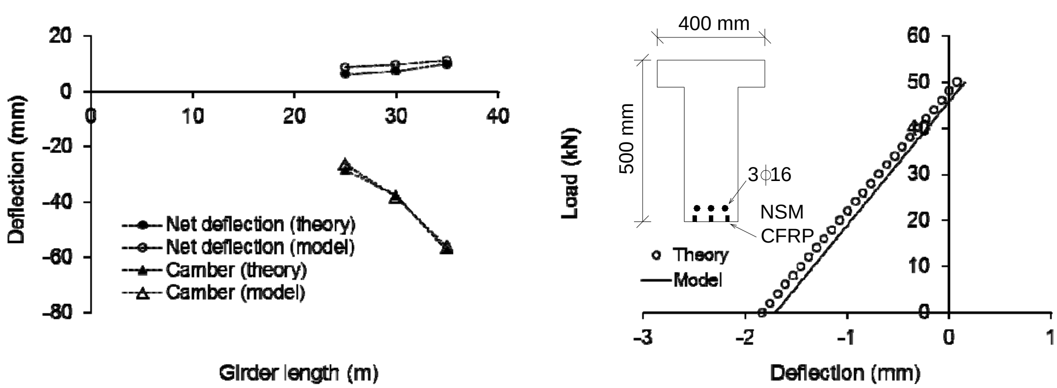


Figure 4: Finite element model developed (cutaway view)

Displacement compatibility was assumed among all constituent elements and the material properties discussed in Sec. 3.1 were input. The preprocessed bridge girder models were then constrained to simulate a simply supported condition (one end was hinged and the other end was rollered as shown in Fig. 1). The live load model (Fig. 2) was positioned to induce the maximum bending moment along each girder. The number of simulated models was 51, including three loading scenarios (i.e., camber loading only without live load, truck load for unstrengthened girders, and truck load for strengthened girders).

4.2. Validation of Modeling Approach

The proposed modeling approach was validated with theoretical and experimental data. For the case of unstrengthened girder models, camber and net deflections were evaluated against structural analysis solutions as shown in Fig. 5(a). The validation approach for strengthened girders was accomplished based on the experimental program conducted by Taljsten and Nordin [17]. The test program included a reinforced concrete T-beam strengthened with three NSM CFRP rods with a total cross-sectional area of 300 mm^2. The CFRP rods had an ultimate strength of 2600 MPa and a modulus of 150 GPa. The 5.6 m simply supported beam was monotonically loaded and its camber and deflection were obtained. Provided the developed model was valid before concrete-cracking takes place, the experimental data were compared with the model prediction up to a decompression load [Fig. 5(b)]. Overall, the modeling approach demonstrated reliable results.



(a) (b)

Figure 5: Validation of modeling approach: (a) unstrengthened case; (b) strengthened case

5. TECHNICAL DISCUSSION

The solved finite element models generated technical data as to the flexural behavior of the prototype prestressed concrete girders with and without NSM CFRP strips. Discussion is provided in this section.

5.1. Response of Reinforcement

The strain profiles of the steel reinforcement of selected girders are shown in Fig. 6. The development of steel strain was rapid near the end of the girders and stabilized as approaching midspan (i.e., the development length of the L = 25 m girder was 2,063 mm [Fig. 6(a)]). The presence of NSM CFRP reduced steel strain; for instance, a reduction of 2.2% was noticed at midspan of the L = 25 m girder [Fig. 6(b)]. It should be noted that no dramatic change in steel strain was predicted because the load applied was a service load (i.e., DB-24). The effect of post-tensioning levels was depicted in Fig. 6(c). Insignificant differences in strain were noticed within the development-length zone, whereas the level of post-tensioning exhibited an apparent effect beyond the zone. This observation corroborates a stress-sharing mechanism between the prestressing steel and the NSM CFRP. The strain variation of the prestressing steel was influenced by the bonded length of the NSM CFRP, as shown in Fig. 6(d). Strain concentrations were found near the termination point of the CFRP, which may induce premature failure of the installed strengthening system in service. To avoid this technical concern, the bond length of the NSM CFRP is recommended to be sufficiently long (i.e., between 60% and 90% of the span length, α = 0.6 to 0.9).

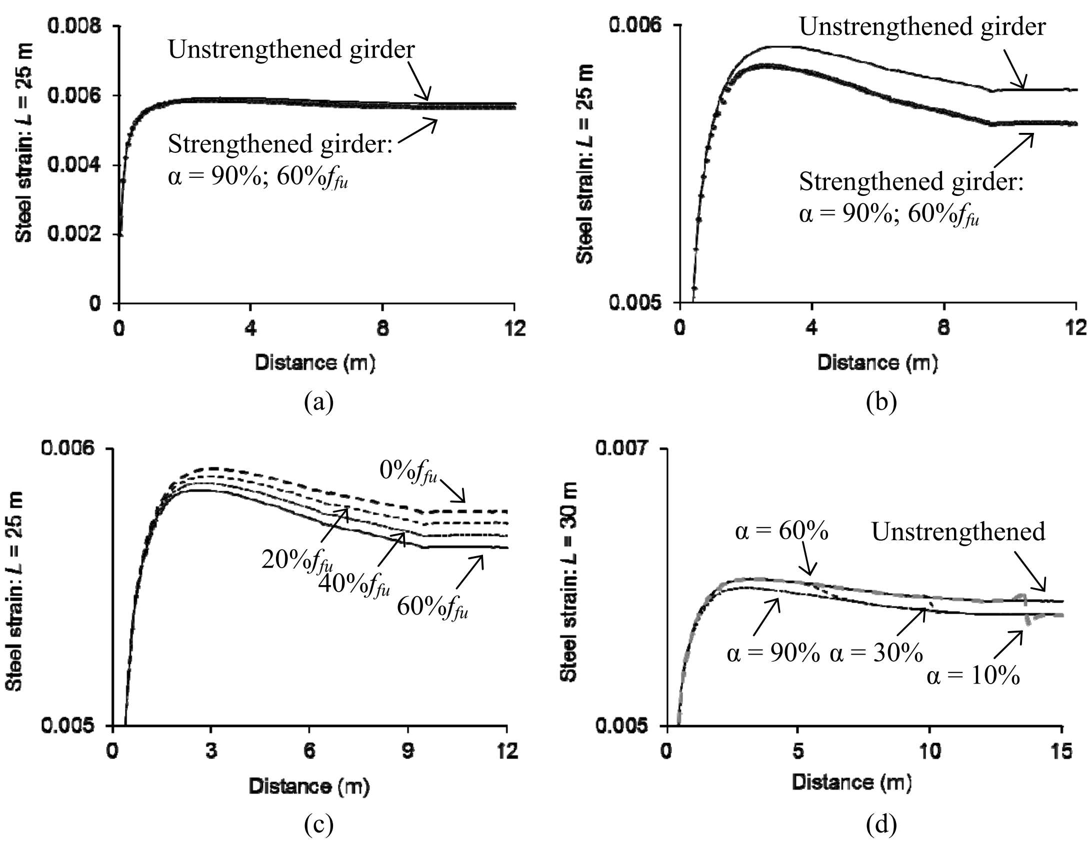
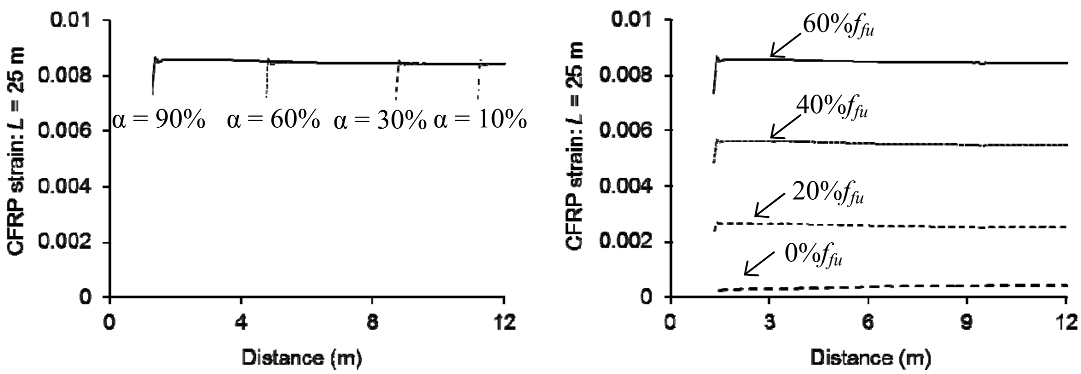


Figure 6: Response of steel reinforcement in strengthened girders under DB-24 load: (a) effect of NSM CFRP strengthening (L = 25 m); (b) effect of NSM CFRP strengthening (L = 25 m) close-up view; (c) effect of post-tensioning level with α = 90%; (d) effect of CFRP bond length (strengthening coefficient α) with 60%f_{fu}



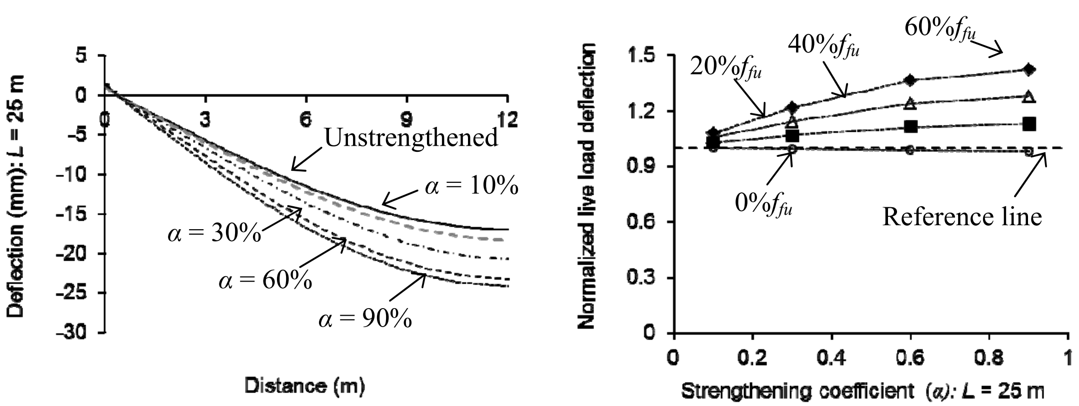
(a) (b)

Figure 7: Response of NSM CFRP: (a) effect of CFRP bond length (strengthening coefficient α) with 60%f_{fu}; (b) effect of post-tensioning level

The profile of CFRP strain for the L = 25 m girder is exhibited in Fig. 7(a), depending upon the strengthening coefficient α (i.e., bonded length of the NSM CFRP). As in the case of the steel strain (Fig. 6), the CFRP strain significantly developed from its termination point and became stable. Regional strain softening was noticed immediately after the strain-development zone. Such a local strain softening effect tended to be reduced with a decrease in post-tensioning force [Fig. 7(b)].

5.2. Deflection of Girders

Figure 8(a) reveals the deflection profile of the girders with various strengthening coefficients. The camber of the prestressed concrete girders was predicted (i.e., negative deflection). With an increasing CFRP-bonded length (or an increase in the strengthening coefficient), the upward deflection proportionally increased up to α = 60% beyond which such an increasing tendency in camber was reduced (in other words, the camber of the girders with α = 60% and 90% was similar). Figure 8(b) shows the effect of a post-tensioning level on enhancing girder deflections. The normalized deflection was defined by a ratio between the upward deflection of a strengthened girder and that of an unstrengthened counterpart. The difference between the unstrengthened girder and the strengthened girder without post-tensioning (0%f_{fu}) was not observed, which means that the serviceability of the strengthened girders without post-tensioning was not improved. Substantial enhancement in deflection was, on the other hand, noticed when the post-tensioning level increased, as reported in Fig. 8(b).



(a) (b)

Figure 8: Response of girders: (a) deflection profile under live load with a post-tensioning level of 60%f_{fu}; (b) normalized live load deflection with post-tensioning level

6. RELIABILITY EXAMINATION

A preliminary investigation into structural reliability was conducted using the concept of safety index (β) to assess the effect of post-tensioned NSM CFRP on the response of the strengthened girders:

$$\beta = \frac{M_n - M_E}{\sqrt{\sigma_n^2 + \sigma_E^2}} \tag{1}$$

where M_n and M_E are the nominal flexural resistance and the load effect induced by DB-24 (wheel load), respectively; and σ_n and σ_E are their standard deviations. The strain compatibility method was employed to determine the nominal flexural resistance of each girder (M_n), while structural analysis theory provided the unfactored load effects (M_E). The standard deviations were estimated as per previous research: coefficients of variation for prestressed concrete girders and live load are 0.075 and 0.18, respectively [18]. As shown in Fig. 9, the safety indices of all the strengthened girders were positioned at around β = 12. Such a high safety index value is attributed to the fact that the girders were loaded in service. Another thing to note is that the post-tensioned NSM CFRP resulted in a uniform level of reliability, irrespective of post-tensioning levels.

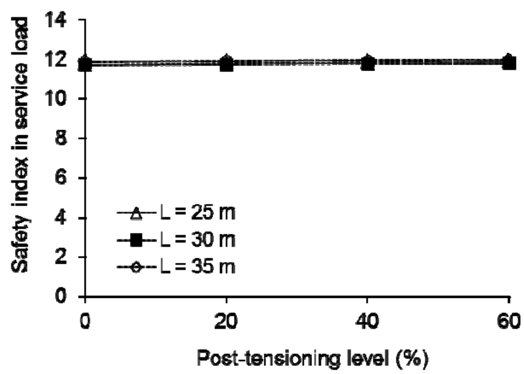


Figure 9: Safety index with post-tensioning level

7. CONCLUSIONS

This paper has discussed the flexure of prestressed concrete girders strengthened with post-tensioned NSM CFRP strips under a service design load. A three-dimensional finite element approach was proposed and validated with theoretical and experimental responses. A preliminary reliability study was conducted. The following conclusions are drawn:

- The post-tensioned NSM CFRP reduced the level of stress in the internal prestressing strands because of a stress-sharing mechanism. Strain concentrations were noticed in the vicinity of the CFRP termination.
- The CFRP-bonded length represented by a strengthening coefficient α was an important factor to consider when implementing this strengthening method on site. It is recommended that the coefficient be in between 0.6 and 0.9.
- A uniform level of reliability was observed for all the girders strengthened with post-tensioned NSM CFRP. Further research in this area is recommended to develop load and resistance factors dedicated to existing bridge girders, with or without the presence of damage, and to those strengthened with post-tensioned NSM CFRP.

Acknowledgements

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Institute of Construction Technology that owns the patented strengthening method presented in this study.

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