INVESTIGATION OF SEISMIC PERFORMANCE AND RELIABILITY ANALYSIS OF PRESTRESSED REINFORCED CONCRETE BRIDGES

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ABSTRACT

Given the vital importance of bridges in life arteries, safety of these structures against destructive agents such as earthquake is of utmost importance. Using pre-stressed columns in bridges will improve their seismic response, because these columns have high displacement capacity during earthquake and a small permanent displacement after earthquake. Therefore, the need for further study on these structures is felt more than ever. In this paper, firstly, pre-stressed columns were analyzed under reciprocating static load using OpenSees software and results show that pre-stressing bridge columns will improve the quasi-static response of columns and column section bearing. Below, we examine the reliability analysis of pre-stressed bridge samples against force of the earthquake and the effect of different random variables on reliability of bridge. The results show that structural damping and earthquake magnitude have a significant effect on reliability of bridges. Changes in characteristic strength of concrete at ultimate limit and mean resistance of section, effect significantly on reliability of bridge structure.

Keywords: Concrete Bridge, Pre-stressed concrete structures, seismic performance, finite element analysis, Structural reliability.

1. INTRODUCTION

One of the important steps in development of each country is to construct roads and highways. The bridges as key components of arterial network of a country roads have unique and important role in economic, social, political and military fields. Damages caused by recent earthquakes, express necessary measures for earthquake resistant design and further study and research in order to better understand the seismic behavior of bridges. Earthquakes in the last two decades in United States, Japan and Turkey showed that many of bridges have had bad behavior due to poor design of components even using the latest research achievements in this area and compiled regulations [1]. Examining the concrete bridges built in the world shows that, these types of bridge are replaced with existing steel bridges, and using pre-stressed methods since its development has been growing rapidly and a lot of researches have been reported on pre- stressed concrete structures [2]. Pre- stressed concrete structures are attractive alternatives for long-span bridges and have been used throughout the world since 1950. Widespread application of pre-stressed concrete in buildings, military structures and civil infrastructure has been increased generally, being aware of principles, practices and developments in design and manufacturing [3]. Billington and Yoon [4] in 2004 demonstrated that using pre-stressing systems can reduce significantly permanent displacements and cracks. Mahin et al [5] provided a new approach in order to reduce permanent displacements generated in conventional concrete columns. They do this through placement of pre-stressed non-attached cable in the center of light concrete columns. Wang et al [6] studied on regular, attached pre-stressed, non- attached columns and hybrid system in two modes of prefabricated and concrete. Kim et al. [7] provided analytical model for normal and pre-stressed prefabricated hollow columns with an equivalent section that has the same moment of inertia with hollow circular or hollow rectangular sections. They concluded that pre-stressing increases bearing and reduces permanent displacements. The probabilistic design presented herein is towards a numerical approach to the safety analysis of a simply supported post-tensioned concrete bridge beam, within an acceptable probability that the given structure will not fail during its intended life [8]. Haukaas [9] performed research work on the finite element reliability and sensitivity methods for performance-based engineering". He developed a modern and comprehensive computational framework for a nonlinear finite element reliability analysis. Moreover, much advanced research work on this subject has been reported in the literature [10]. Frangopol and Imai [11] studied the reliability of suspension bridges located in Japan, when under wind and earthquake loads. They applied spectral analysis and evaluated the reliability of the structure. The mechanical and geometrical properties of the sections were taken as the random variables. In this paper, the behavior of pre-stressed and attached columns under seismic loading as well as seismic reliability of arch concrete bridge using the finite element method are studied.

2. THEORY OF THE PROBLEM

The equation of system motion affected by earthquake forces can be expressed as follows:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{P_{eff}(t)\} \quad (1)$$

In this equation [M] is concentrated mass matrix, [C] is damping matrix, [K] is stiffness matrix, $\{P_{eff}(t)\}$ is earthquake effective force vector, $\{u\}$ is displacement vector, $\{\dot{u}\}$ is velocity vector and $\{\ddot{u}\}$ is acceleration vector. Calculating the response of bridge structure of equation (1) is resolved using standard modal conversion technique.

$$q_n(t) + 2\xi_n\omega_n q_n(t) + \omega_n^2 q_n(t) = -\Gamma_n \ddot{u}_g(t) \quad (2)$$

In this equation, $q_n(t)$ is normal coordinates, ξn is structural damping percent of nth mode, ω_n is natural frequency of nth mode, Γ_n is modal distribution coefficient and $\ddot{u}_g(t)$ is the vertical acceleration caused by earthquake. Equation (2) can be expressed as follows:

$$\frac{q_n(t)}{\Gamma_n} + 2\xi_n\omega_n \frac{q_n(t)}{\Gamma_n} + \omega_n^2 \frac{q_n(t)}{\Gamma_n} = -\ddot{u}_g(t) \quad (3)$$

Assuming $\frac{q_n(t)}{\Gamma_n} = D_n(t)$, the equation (2) is expressed as follows:

$$D_n(t) + 2\xi_n\omega_n D_n(t) + \omega_n^2 D_n(t) = -\ddot{u}_g(t) \quad (4)$$

Equation (3), is system motion equation with a single degree of freedom and it can be easily solved using numerical methods. Solving equation (3) we can obtain structural displacements in different modes. Since the response of total structure and applied would be calculated as follows.

$$\{u(t)\} = \sum_{n=1}^{N}\{u_n(t)\} = \sum_{n=1}^{N}\Gamma_n\{\phi_n\}D_n(t) \quad (4) \quad \text{and} \quad \{f_s(t)\} = [K]\{u(t)\} \quad (5)$$

Failure due to bending compared to other modes of failure is the most common type of failure mode in reinforced concrete structures. Thus, in the present study, reliability of structure is calculated for flexural failure. Bridge structure is modeled using finite element software as continuous beam with Beam two-dimensional element. Dead load is distributed evenly as linear load along elements. Vertical seismic accelerations are considered as earthquake load on structures. Bridge structural reliability analysis was conducted using FOSM Method. For calculating the reliability of bridge structure, a certain percentage of ultimate bending strength is considered as a resistance force and bending moment caused by earthquake is considered as force due to loading. Bridge structure is analyzed for a number of earthquakes as 50 accelerogram and finally, mean and standard deviation values of bridge structure reactions are calculated according to results of analysis. In general, if equations related to probability distribution functions of random variables are available, the reliability of structures will be calculated using integral equations listed in Equations 6 and 7.

$$\mathrm{P_f} = 1 - \mathrm{R_0} = 1 - \int_{-\infty}^{+\infty} \mathrm{f_s}\,(\mathrm{s})[1 - \mathrm{F_R}(\mathrm{s})]ds = \int_{-\infty}^{+\infty} f_s\,(s)F_R(s)ds \quad (6)$$

$$\mathrm{P_f} = 1 - \int_{-\infty}^{+\infty} \mathrm{f_R}\,(\mathrm{r})\mathrm{F_s}(\mathrm{r})dr \quad (7)$$

Where $\mathrm{P_f}$ is structural failure probability, $\mathrm{R_0}$is reliability of structures, $\mathrm{f_x}(\mathrm{x})$ is probability density function and $\mathrm{F_x}(\mathrm{x})$ is cumulative distribution function. The failure probability function can be expressed as the following equation:

$$P_f = \emptyset\left(\frac{\mu_S - \mu_R}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) \quad (8)$$

In equation 8, $\emptyset$ is standard normal distribution function, μ_S is mean force applied on structure, μ_R is mean structure strength, σ_R is structure standard deviation and σ_S is standard deviation value of loading. If structural reliability index is $\beta = \frac{\mu_g}{\sigma_g}$, therefore, structural failure probability can be expressed as: $P_f = \emptyset(-\beta)$ (9)

Finally, the reliability index of structures is expressed by Equation 10. $\beta = -\emptyset^{-1}(P_f)$ (10)

Ultimate strength limit state and allowable stresses limit state are considered as limit conditions. For these two cases, the limit conditions are defined as follows: $\varepsilon_{cu} \leq 0.0035$

In this equation ε_{cu} is compression stress of concrete tension area. For limit requirement, security margin equation is considered as: $g_u = \alpha M_u - M_s$ (11)

Where, M_u is sectional ultimate resistance moment, M_s is loading moment and α is a coefficient smaller than 1 that each stage represents the percentage of ultimate moments dedicated to counter loading moment due. For allowable limit stress, the below equation is established: $f_{ct} \leq f'_{ct}$ (12)

Where, f_{ct} is tension stress of concrete tension area and f'_{ct} is allowable tension stress of concrete. Security margin equation for this state is considered as: $g_e = \alpha M_e - M_s$ (13)

3. STUDYING PRE-STRESSED COLUMNS UNDER RECIPROCAL QUASI-STATIC LOAD

Loading is done according to Figure 1. Loading pattern by controlling displacement for applying load of reciprocating wheels. Loading continues until the load of reaches to maximum value of 0.85.

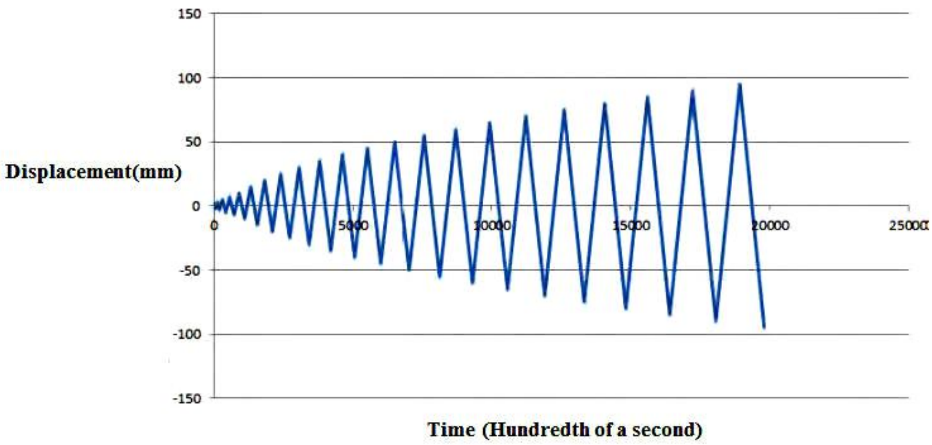

FIGURE 1. The procedure of loading pattern and experiment

Cross-section of columns is 50 × 36 cm for typical and pre-stressed columns. 26 armatures of 12 mm diameter were used in conventional concrete columns round cross-section and six wires of 5 mm diameter were used around a wire with the same diameter for pre- stressed section. Lateral load applied point is 1550 mm above the column fixed base and studying is based on flexural failure. Concrete design strength is 32.5 MPa and conventional bars yield strength is 335 MPa and ultimate stress of pre-stressed tendons is 1860 MPa. Constant compressive force of 576 KN is applied to simulate the gravity loads applied at the time of service at the top of column. Modeling is carried out using OpenSees software where the structural analysis is done using finite element method. Nodes are defined in OpenSees software for pre-stressed system and a graphical form of nodes were drawn using OPS software in order to ensure the accuracy. All parts of fiber section move fully coherent, total cross section is defined using fiber section that is able to define simultaneously bars, tendons and concrete with different stress-strain diagram in different locations of a cross-section. According to the fact that in pre-stressed systems tendons are involved with concrete, therefore, it shows the necessity of using a single fiber. However, the materials used in fiber cross section must be defined previously. Material Initial Stress is used in order to apply pre-stressed force.

Also, effects of growth and Pinching of Hysteresis curve and considering Boushinger principle and the ability to change are features of this type of material. Figures 2 and 3, show the results of conventional and pre-stressed concrete column analysis. These figures are related to proposed model using the materials. As can be seen in Figure 2, it is found that permanent displacement is reduced greatly and bearing capacity is increased. Also, according to Figure 3, which corresponds to pre-stressed post- tension concrete column, permanent displacement is reduced and bearing capacity is more than post- tension state.

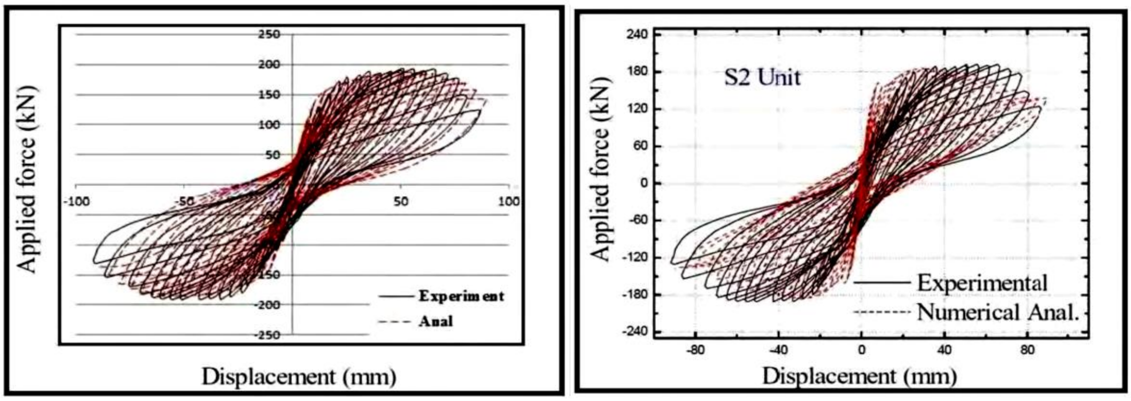

FIGURE 2. Non- attached pre-stressed hysteresis curve diagram

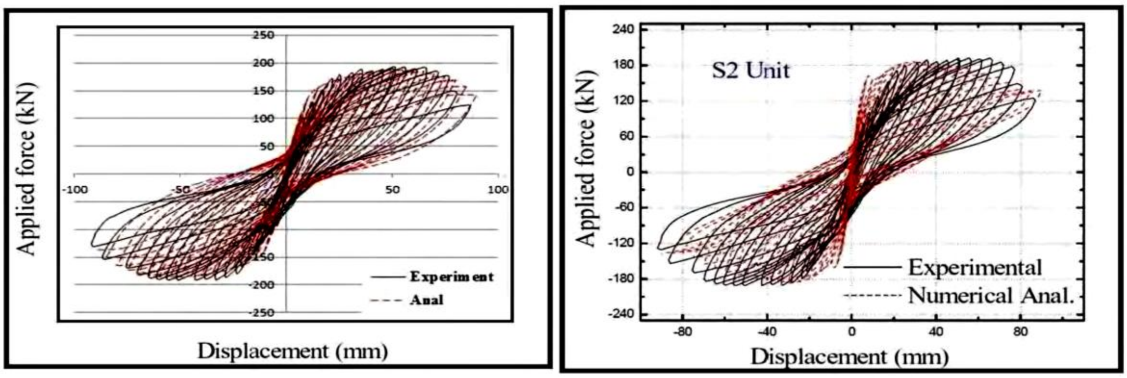

FIGURE 3. Attached pre-stressed hysteresis curve diagram

4. THE RELIABILITY OF BRIDGES AGAINST EARTHQUAKE-INDUCED FORCES

According to partial surveys conducted on reliability analysis of bridge structures against earthquake forces, in this section, the reliability of an arch pre-stressed concrete bridge against earthquake forces are examined. In this section, the mechanical properties of materials, geometric characteristics of sections, structural damping rate, magnitude and maximum acceleration of earthquake are considered as random variables. The bridge is modeled as a continuous beam and linear system behavior is assumed. Vertical accelerations of earthquake are considered as loads applied on bridges for time history analysis of bridge structure during an earthquake and probability density distribution function of random variables are extracted from existing sources and normal probability distribution function is assumed for those variables that had no sources. The examined pre-stressed arched bridge sample includes a three-span bridge with central span of 125 m length and first and second lateral span with length of 55.35 and 45 meters, respectively.

Figure 4 shows the changes of reliability index of bridge structure based on standard deviation of concrete characteristic strength for final resistance limit state. Each curve corresponds to a certain percentage of section ultimate strength. As can be seen, a bridge reliability index change is not considerable per high percentage of cross-resistance but structural changes reliability index is increased as cross-resistance decreased. The reason is that effects of fluctuations arising from changes of concrete characteristic strength on reliability index against section ultimate resistance are trivial. Increasing the percentage of concrete ultimate strength that is used to deal with the external load, the characteristic resistance of concrete changes effects on reliability index is decreased. Figure 5 shows the changes of bridge structure reliability for allowable stress limit state. In limit state, due to the low level of resistance, total resistance of section is considered to cope with the effects of external loading. As can be seen from diagram, changes in specific strength of concrete does not effect on bridge structure reliability index. The interesting point is percentage of structural damping effect because 3 percent increase of structural damping results in double increase of structural reliability index.

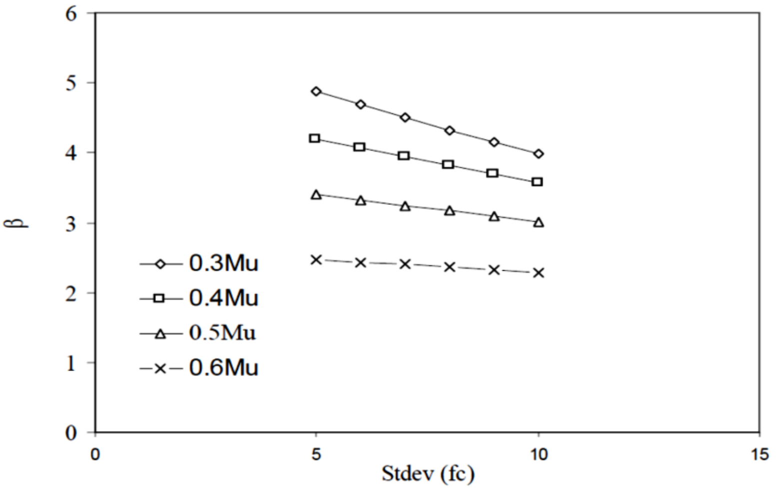

FIGURE 4. The effect of characteristic resistance changes on reliability index for damping percentage (5% ultimate strength limit state)

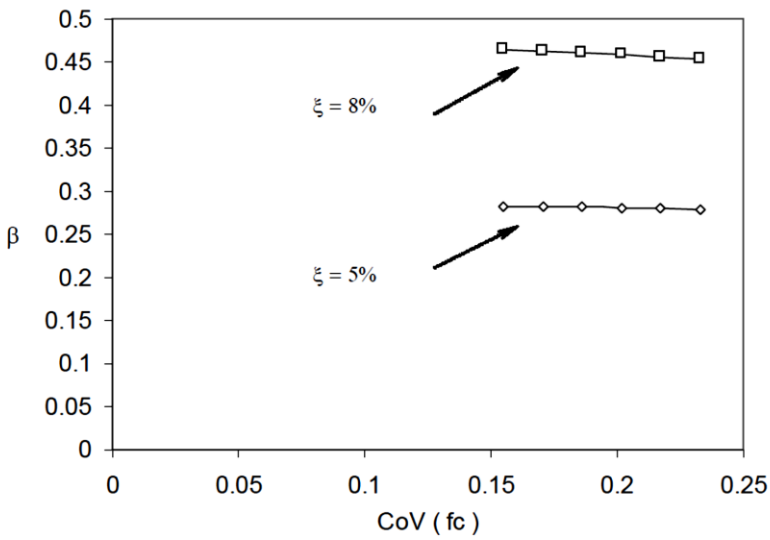

FIGURE 5. The effect of characteristic resistance changes on reliability index (allowable stress limit state)

Figure 6 shows the effect of structural damping changes on reliability index of bridge structure for ultimate strength limit state per different percentages of section resistance. As can be seen from the figure, changes of structural damping effect are evident on reliability changes of bridge structure. The changes of lower amounts of section resistance are more than high levels of section resistance, so that increasing resistance results in curve section tendency to flat and horizontal state.

Figure 7 shows the percentage of structural damping effect changes on reliability index of bridge structure in allowable stress limit state. As can be seen, the effect of random variable changes on reliability index changes in limit state is somewhat obvious. In a general conclusion we can say that the important random variable of this issue is bridge structural damping percentage.

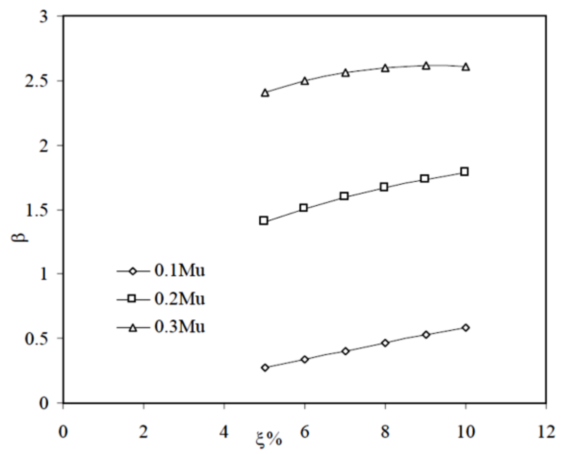

FIGURE 6. Changes of bridge structure reliability index per changes of structural damping percentage, ultimate strength limit state

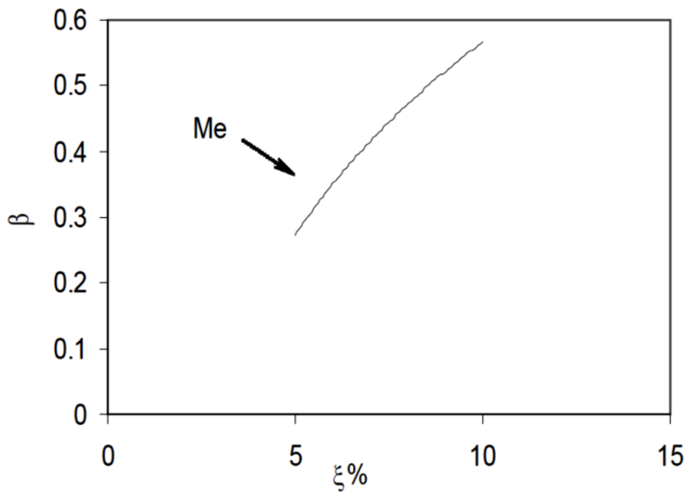

FIGURE 7. Changes of bridge structure reliability index per changes of structural damping percentage, ultimate allowable tension limit state

5. CONCLUSION

The study examines behavior of attached and non- attached pre-stressed column under reciprocating quasi-static load by controlling the displacement using the finite element model and effects of concrete characteristic strength parameters and the percentage of structural damping on bridge structure reliability. the results show that using new materials and direct apply of pre-stressing force will increase the accuracy of analytical models. It was found that pre-stressing improves the quasi-static response of concrete columns and meets concrete weakness largely in tension. In the case of non- attached pre-stressing, it can also be expressed that pre- stressing increases section bearing significantly and on the other hand, it reduces permanent displacement. the structural damping percentage is one of the key parameters in seismic design of bridge structures and results show that controlling this parameter is necessary for safe design. In most cases, except in the case of structural damping percentage for other random variables, fluctuations of bridge structure reliability index per changes in random variables for low percentages of section resistance and high percentages of section resistance is trivial and nearly tends to be uniform. changes of concrete characteristic strength in allowable tension limit state does not effect on reliability of bridge. But in ultimate limit state and mean resistance level, it effects significantly on structural reliability and fluctuations of bridge reliability caused by changes of concrete specific strength are less compared to fluctuations arising from changes of structural damping.

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