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The Importance of Determining Damage Levels of the Bridges in Non-Linear Dynamic Analysis

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ORIGINAL ARTICLE

ABSTRACT: During past earthquakes, different modes of damage were observed in bridges; consequently in seismic evaluation of these structures, various Indexes were used to determine vulnerability of the structures against earthquake vibrations. In this paper, damage indexes of structural elements of bridge are introduced and suggested definitions for structure damage state are stated. Then, a three span bridge is analyzed using OpenSees non-linear analysis software, considering three-dimensional model under earthquake load and non-linear behavior. After calculating necessary outcomes of the elements and nodes, damage indexes of damage at the foundations and columns level were measured. The model is able to calculate responses and damage indexes of supports and joints. Using this model, damage level of bridge structure is determined based on tables, which determine necessity of retrofitting. Based on the result, decisions made based on each criterion are compared. The results show that exact specification of damage indexes for the estimation of the vulnerability of structures (bridges here) is very important.

Keywords: OpenSees Model, Bridge, Damage levels, Reinforcement, Stiffness

INTRODUCTION

Damage indexes determine the amount of energy absorbed by the material, used by materials or is remained in element. The concept of damage index can provide tools to quantitate damage rate and estimate it before damage. It offers the opportunity to select seismic retrofitting and its Implementation methods.

Damage indexes of the bridges

In a bridge with reinforced concrete column under horizontal earthquake loading, a reduction in strength and stiffness of inelastic range can be seen in the forces exerted. These Forces start with flowing in the foundation, anchorage failure or overlapped patches or even shear failure in severe damages. Severity of the influence of these modes mostly depends on structure detailing in structure elements.

Damage index is defined on bridge structure level, and in most cases it depends on the function of bridge column Damage index may be based on the situation in which pressure strain of reinforced concrete column can reach the final strain and be considered in lower level of damage index in which compressive strain of concrete is in maximum stress. In another word, damage index can be defined in tensile Reinforcement of column, with strain limit and corresponding stress level of the index. In supports with expansion joint, width of seat and size of support is important and instability and lack of accurate placement is a function of these two. High horizontal displacement of deck increase vulnerability of expansion support to collapse. However, damage index can also be considered as ratio of demand to capacity of structural member. This index is defined as "the ratio of rotation demand of bridge column to the rotation capacity of member in terms of percent" that can be expressed after identifying the statue of member in damage limit or lack of need to retrofitting.

Damage levels

Tables 1-4 represent damage states of bridge structure with ductility limitation, comparing the demand and capacity, compressive concrete and tensile reinforcement, fixed support and expansion support. The idea of Park at al. is shown in table 2 (Kim and Feng). Damage index of 0.1 is used when minor bending crack is occurred before placing longitudinal reinforcement of column and is recoverable. Damage index of 0.4 is for crushing of concrete cover by flexural and shear cracking after longitudinal reinforcement; the damage is not recoverable. Damage state of 1 represents considerable failure of longitudinal reinforcements.

Table 3 represent damage indexes of compressive concrete and tensile reinforcement, in which ρ_s is transverse reinforcement ratio, f_{yh} flow stress of transverse reinforcement, ε_{sm} reinforcement bending in maximum tensile stress, $f'c$ compressive strength of concrete cover (Kima et al., 2005).

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Table 1.damage states of bridge column suggested by Dutta, Mander.

Damage state	Description	Displacement limit (designed for seismic load)	Displacement limit (designed for Non-seismic load)	demand ductility
No damage	First Yielding	0.005	0.008	1
Slight damage	In crack and failure	0.007	0.01	2.01
Moderate damage	Lack of bracing	0.017	0.025	6.03
Extensive damage	First failure of column	0.025	0.05	11.07
Complete damage	Columns failure	0.05	0.075	23.65

Table 2. Relationship between defined damage index of bridge column and damage State.

Damage state	Minimum damage index		
	Park et al.	Stone and Taylor	Williams
Repairable damage	0.1	0.11	0.12
Irreparable damage	0.4	0.4	0.39
Failure	1	0.77	1.28

Table 3. Failure criterion

	Failure criterion (ε_{tu} ε_{cu})
Concrete (Compressive and shear)	$0.004+\frac{1.4\rho_s.f_{yh}.\varepsilon_{sm}}{f_c'}$
Steel (tensile)	0.1

Damage index of compressive concrete in damage time is based on the situation in which compressive strain of concrete reach final strain of concrete. Similarly, damage index of tensile reinforcement in damage time is in way that tensile strain of tensile reinforcements reaches final strain of reinforcements. Damage index of compressive concrete and tensile reinforcement can be suggested as follow:

Compressive: $$D.I = 1 - ftg_c\left(\frac{2\varepsilon_{cu}-\varepsilon_{cs}}{2\varepsilon_{cu}}\right)$$

Tensile: $$D.I = 1.2\left(\frac{\varepsilon_{ts}}{2\,ftg_r\varepsilon_{tu}}\right)$$

where ftg_c and ftg_r are fatigue parameters of concrete and reinforcement, respectively, and are calculated using following formula:

$$ftg_c = 1-0.3AD_C \qquad AD_C = \sum\frac{1}{N_2 f_c}$$

$$ftg_r = 1-0.3AD_r \qquad AD_r = \sum\frac{1}{N_2 f_r}$$

where ε_{cu} and ε_{cs} are final strain and compressive strain of concrete and ε_{tu} and ε_{ts} are final strain of tensile reinforcement and tensile strain, respectively. N_2 of concrete is the whole cycles of failure time of concrete and N_2 of reinforcement is the whole cycles of longitudinal reinforcement failure time.

Based on table 4, ductility limit of curvature for columns are μ=1to μ=7 for low damage to total damage limit of columns (Choi, DesRoches, and Nielson, 2003).

Description of the model

Configuration of a bridge models with joined girder is represented in figure 1. The bridge contains 3 spans of 12.2, 24.4 and 12.2 meter, respectively. Width of each span is 15 meters. Frames include 3 columns and cap beams on the columns. Since the cross-section of composite deck is very difficult and their composition acts as rigid connection, Stiffness structures don't play significant role in seismic response of the bridge (Nielson). Although the response of Stiffness is not sensitive, sensitivity of response to mass is inevitable.

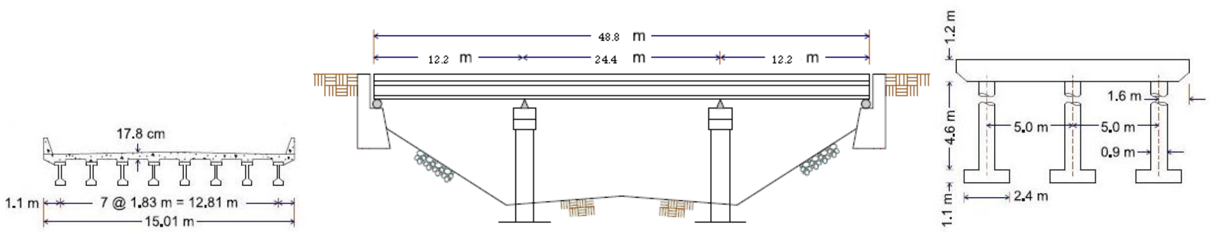

Figure 1.bridge configuration with pre-stressed concrete girder and column and cap beam profile

Material model

Model of materials used in bridge columns for concrete core is compressive strength of 28 days 250 kg/cm^2, and for concrete cover the compressive strength is 210 kg/cm^2 in OpenSees bridge model (Mazzoni, McKenna, Scott, Fenves, et al, 2006). "Uniaxial material Concrete01" is used for confined and unconfined concrete. The model considers no tensile stress for the

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concrete. For confined concrete (concrete core), the strain of 0.005 is used in maximum stress and strain 0.014 is used in final limit. Longitudinal reinforcement of "uniaxial material steel01" are modeled by Bi-linear stress-strain relation and considering strain hardening. Two line curves have $210*10^4$ slope in which in the first level flowing stress is 4000 kg/cm^2 and slope of strain hardening is 0.01. Stress-strain relation of reinforced reinforcement is symmetric in tensile and stress. However, materials used in elements of the head of the base are corresponding to column. Specification of used material is shown in figure 2. In lateral support, the crack is 5 cm, selected by tangent hardness of $200*10^4$kg/cm^2 in "uniaxial material ElasticPPGap" and considering compressive forces. Figure 3 represent lateral support model.

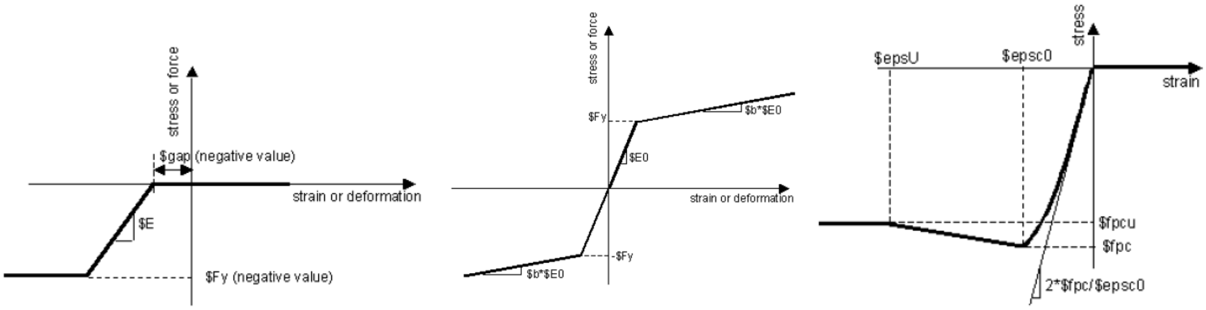

Figure 2. material parameters: a) Concrete01, b) Steel01, c) ElasticPPGap

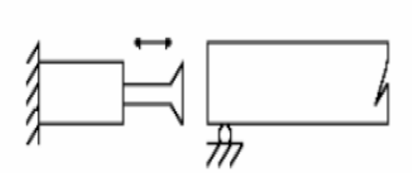

Figure 3. Deck- Abutment interaction simulation model

Configuring fiber elements

The diagonal of all columns is 90 cm. The section includes longitudinal reinforcements of ϕ 28with concrete cover with 5 cm thick placed on spiral tight. Fiber configuring of column section is shown in figure 1. The number of fibers influences analysis accuracy and time. To determine optimal number of fiber elements, moment-curvature analysis of the column was done using Opensees software, and minimum amount of divisions and layers were recognized to achieve converge results. Consequently, 10 layers were determined for concrete column core and 2 layers for concrete cover. Using moment-curvature relation, fiber element division number was compared and concluded that increasing layers increases Stiffness and section strength. In higher layers the results are more accurate. In the case of the number of layers exceed 10 layers of core and 2 layers of concrete cover, no significant difference is observed in results. The similar analysis is used for cap beam. Optimal division of fibers in cap beam is represented in figure 4.

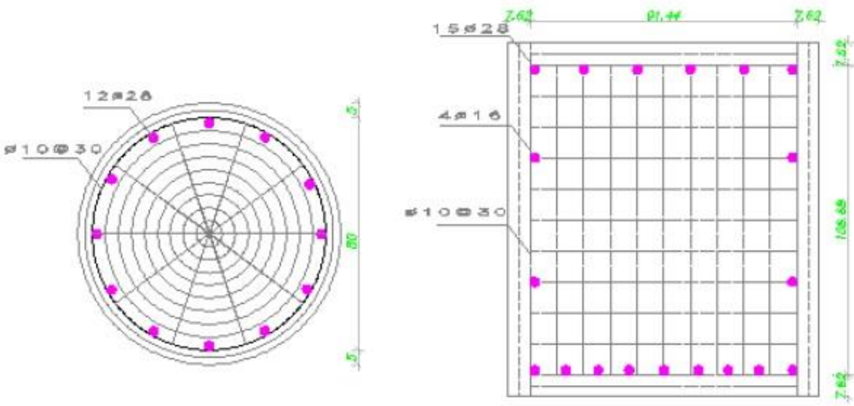

Figure 4.optimal division of element fibers of cap beam and column.

Element configuring

Selecting elements of columns

For dynamic analysis, distributed plasticity model is used for bridge columns. For distributed plasticity in throughout the column, "Disp Beam column" element is used in OpenSees model. In this model, element displacement with distributed plasticity is linear curve distribution (Mazzoni, McKenna, Scott, Fenves, et al, 2006). This type of element is also used in cap beam.

Analysis model

Since inelastic model can have calculation errors, model efficiency should completely be considered. To determine various elements of bridge columns, the number of fibers and time should be determined in a way to achieve convergence results that can be proved (Sadrossadat Zadeh, and Saiidi, 2007).

Analysis and Integration method

In dynamic analysis of the bridge using time history method, two elements of Tabas earthquake with acceleration of 0.65g were compared. This longitudinal record with 30% of latitude records were applied to structure simultaneously, and convergence control of time interval variable was determined. Time interval of 0.002 second was selected based on minimum time interval needed for convergence. Fundamental period of the structure was 0.75 second. Average analysis time for a seismic analysis of 50 second earthquake (Tabas earthquake) was about 20 minutes compared to 0.65 g stimulation with 1.8 GHz processor. Newmark-beta method was the integration method used for analysis (β=0.25 and γ = 0.5). System profile SPD is the equation system and its solution. In this research, Curvature ductility, displacement ductility, tensile reinforcement, compressive concrete of column, and deck displacement are considered among defined indexes.

Results of analysis and studying indexes

Moment-curvature analysis

Moment-curvature relation is obtained by a strain form of cross section, including balance between axial load and internal forces of concrete or steel. To analyze moment-curvature, fiber section of zero-length section elements is under a fixed axial load and increasing bending moment. Results of the analysis reports yielding curve as $\varphi_y = 6.8 \times 10^{-5} cm^{-1}$.

There is variety of quantities to define limit states of concrete reinforced columns. The quantities include lateral displacement, displacement ductility μ_Δ , and curvature ductility μ_φ. In the following formula, μ_φ is defined as:

$$\mu_\phi = \frac{\phi_{\max}}{\phi_y}$$

This amount is the maximum real curvature divided by yielding time or yielding curvature of maximum longitudinal reinforcement.

Curvature ductility of column μ_φ

According to column ductility demand definition ($\mu_\phi = \frac{\phi_{\max}}{\phi_y}$) NO. 1 element of column Curvature ductility in time is drawn (figure 5). Based on the mentioned damage state, the maximum ductility of element 1 of column Curvature in 11.226 second is μ_φ=4.67. Based on damage state suggested by Dutta, Mander, this failure is average.

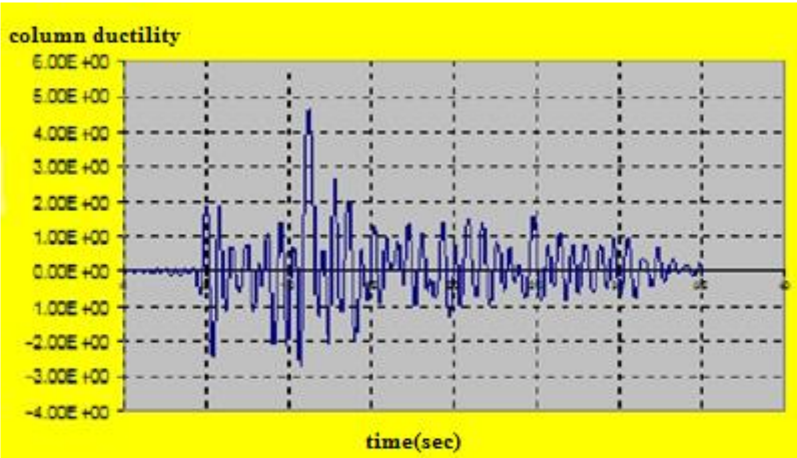

Figure 5. Curvature ductility of column during earthquake

Displacement ductility of column μ_Δ

According to highway bridge seismic retrofit regulations (FHWA), and due to the lack of concrete confinement, displacement ductility of longitudinal reinforcement buckling is 3 (FHWA). Hence, in this study this criterion is used. Limited states of displacement ductility should be changed to equivalent curvature ductility. Ductility levels change is defined as follow in FHWA:

$$\mu_\phi = 1 + \frac{\mu_\Delta - 1}{3\frac{l_p}{l}(1 - 0.5\frac{l_p}{l})}$$

where l is column joint length, and l_p is plastic joint length, obtained by the following relation:

$$l_p = (0.08)l + 9d_b$$

d_b is diagonal of longitudinal reinforcement. Based on the following relation, μ_ϕ is calculated as:

$$l_p = (0.08)\times 460 + 9 \times 2.8 = 62cm \quad ,$$

$$\mu_\phi = 1 + \frac{3-1}{3\frac{62}{460}(1 - 0.5\frac{62}{460})} = 6.3$$

Limit states of new curvature ductility for Slight, Moderate, Extensive and Complete failure is 1, 1.58, 3.22 and 6.84, respectively. Therefore, Complete failure is expected.

Studying fibers

Concrete core: Regarding total cycles of compressive concrete failure and Compressive strain in each level of analysis, compressive concrete damage index is determined and compared with suggested failure criteria of tables 1, 2 and 3

$$D.I=1-ftg_c(\frac{2\varepsilon_{cu}-\varepsilon_{cs}}{2\varepsilon_{cu}})\longrightarrow D.I=1-ftg_c(\frac{2\times-0.014-\varepsilon_{cs}}{2\times-0.014})$$

Tensile reinforcement

Regarding total cycles of reinforcement failure in tensile and tensile strain of reinforcement in each level of analysis, damage index of tensile reinforcement is determined and can be compared to suggested failure criteria of tables 1, 2 and 3.

$$D.I=1.2(\frac{\varepsilon_u}{2ftg_s\varepsilon_{su}})\longrightarrow D.I=1.2(\frac{\varepsilon_u}{2ftg_s\times0.192})$$

Deck displacement

Figure 6 represents time history of deck displacement under base acceleration stimulation in Tabas earthquake. Maximum longitudinal displacement of deck in 35 second is 12.4 cm.Regarding elastic behavior of deck and continuity of deck in 3 spans, maximum displacement of deck should be less than width of seat in lateral support. According to the considered 5 cm free space, for modeling lateral support (element 7), the width should be at least 17.4 cm.

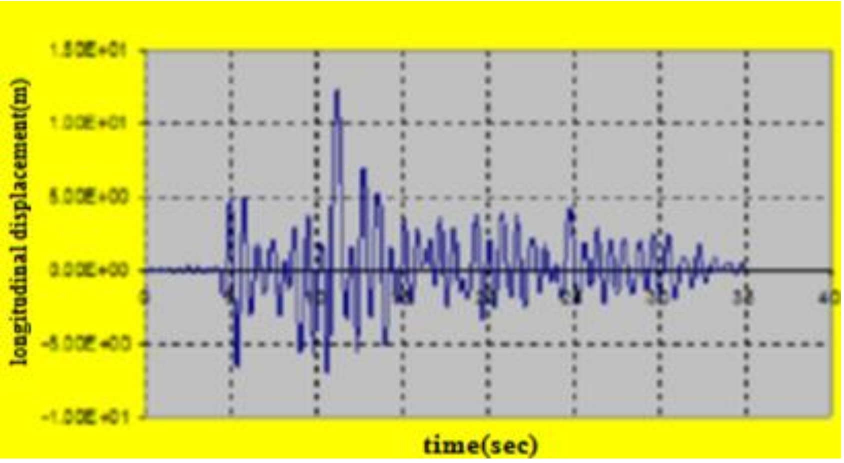

Figure 6. Longitudinal deck displacement diagram in 35 seconds

The allowable compression stress in element 7 (ElasticPPGap), is 300 kg/cm2 (compressive strength of concrete) (figure 7). Force applied to elements of analysis is obtained according to figure 8. It's observed that in interval of 5 and 15 seconds, high amount of force applied to element increase its vulnerability potential.

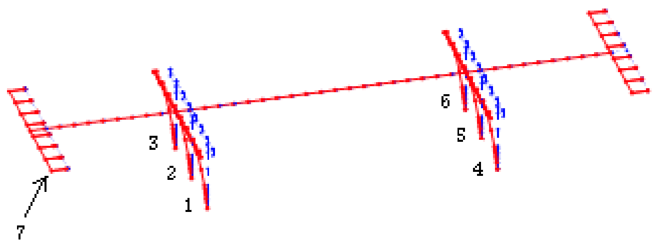

Figure 7. elements configuring

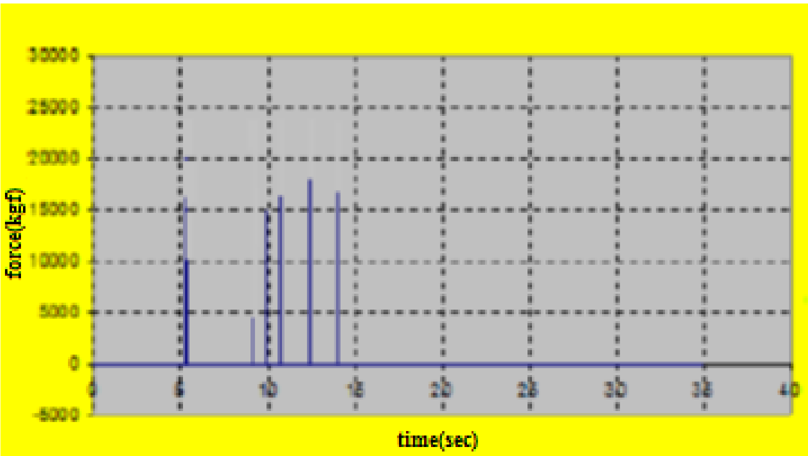

Figure 8. force applied to abutment element in 35 seconds

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CONCLUSION AND SUGGESTION

Estimation of Bridge vulnerability assessment based on damage index provided by the researchers for the typical of structures. If the properties of materials, elements, connections, soil and damping change, it is necessary to know the exact limit state of bridge failures. For curvature ductility of column (in moment-curvature analysis), flow curvature is calculated by used material characteristics. In this analysis, increasing number of layers and shears of fibers has no influence on results of analysis. In non-linear dynamic analysis, time history increases analysis time particularly in Constraints high number of structures. Performance level of bridge is determined by introducing a set of damage indexes in bridges and combining them to achieve accurate results. The main damage index studied in most of the researches in this area focuses on ductility need of column; hence this is emphasized in this paper. It's better for next levels to model support (material characteristics and defining their real behavior), accurately study back wall of abutment characteristics and abutment piles, and interaction between Abutment and back wall.

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