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A new damage index for RC buildings based on variations of nonlinear fundamental period

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SUMMARY

Many vital reinforced concrete (RC) buildings experience moderate or severe earthquakes in their lifetime because they are located in hazardous areas. However, their importance cause to be evaluated by different types of damage functions. In these procedures, structures are usually modelled. These models neither correctly display the effects of the cracks that emerge and plastic hinges nor precisely consider the effects of asymmetric configuration and infill panels. Furthermore, the actual nonlinear dynamic behaviour of existing buildings could be evaluated by assessing nonlinear dynamic characteristics such as the fundamental period. These dynamic characteristics, which are obtained by some field tests such as forced and/or ambient vibration methods, comprise the aforementioned effects. This paper offers a damage index (pattern) for seismic damage assessment of RC buildings based on the variation of the nonlinear fundamental period, which is obtained by field tests. Finally, the seismic situation of existing RC buildings that have experienced an earthquake is precisely and expeditiously assessed by this new damage index.

1. INTRODUCTION

Different local and global damage indices have been proposed to evaluate existing buildings. Each of these indices focuses on the parameters that were obtained by modelling building structures. Structural ductility, storey drift, element and connection rotation, dissipated energy and fatigue of structure are parameters that are considered for damage assessment. An outline of previously suggested damage indices is shown in Table 1. (Only basic articles are cited in Table 1; otherwise many scholars work on this issue.) These parameters theoretically show the actual seismic behaviour of existing structures, but most of the time the data are not precise because they are obtained by modelling. An accurate modelling of the structures of existing buildings that have been damaged by an earthquake is not possible because the distribution of cracks and plastic hinges is not exactly known. Furthermore, the effects of infill panels and architectural configuration (irregularity) on seismic behaviour are not dispensable. Besides, consideration of these effects in nonlinear mathematical or finite-element models is very complicated and time-consuming. Therefore, consideration of the aforementioned parameters does not seem appropriate for damage assessment. In contrast, some parameters represent the actual seismic behaviour of structures with consideration of the aforementioned effects and nonlinear damping ratio, which affects the response of structures to the seismic loads directly (Chopra, 1995), if they are obtained by field tests on existing buildings. These are modal parameters of structures that have been obtained by field tests precisely, swiftly and cheaply (Moshtagh and Massumi, 2009).

In this paper, a correlation between elongation of fundamental period and the Park–Ang damage index is shown. Finally, a new damage index based on this essential correlation is represented. This new damage pattern is important because it comprises fundamental period elongation, which shows the softening of the structure, and encompasses a significant damage index, the Park–Ang damage index. The Park–Ang damage index is crucial because it is based on dissipated energy in the elements

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Table 1. Damage index (overview).

Local damage index		
Cumulative	Non-cumulative	Global damage index
Normalized cumulative rotation (Banon and Veneziano, 1982)	Ductility ratio (Newmark and Rosenblueth, 1971; Ayala and Xianguo, 1995)	Maximum softening (DiPasquale and Cakmak, 1988)
Low cycle fatigue (Stephens, 1985)	Interstorey drift (Sozen, 1981; Roufaiel and Meyer, 1981)	Final softening (DiPasquale and Cakmak, 1988)
Park–Ang damage index (Park and Ang, 1985)	Slope ratio (Toussi and Yao, 1982)	Park–Ang damage index (Park and Ang, 1985)
Energy based models (Elms *et al.*, 1989; Kratzig *et al.*, 1989)	Flexural damage ratio (Roufaiel and Meyer, 1981)	Global damage index (Chung *et al.*, 1987)
	Maximum permanent drift (f and Yao, 1982; Stephens and Yao, 1987)	Roufaiel–Meyer global model (Roufaiel and Meyer, 1987)
	Stiffness damage index (Ghobarah *et al.*, 1999)	

of a structure and their deformations. Also, it weights them according to their importance for global assessment:

$$DI_{P\&A} = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h, \tag{1}$$

where δ_m is the maximum experienced deformation, δ_u is the ultimate deformation of the element, P_y is the yield strength of the element, $\int dE_h$ is the hysteretic energy absorbed by the element during the response history and β is the model constant, parameter, which was suggested to be 0·1 for nominal strength deterioration (Park *et al.*, 1987b).

Since the inelastic behaviour of reinforced concrete is confined to plastic zones in the inelastic damage analysis of reinforced concrete frame (IDARC) program, the following modification to the original model was introduced (Kunnath *et al.*, 1992):

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h, \tag{2}$$

where θ_m is the maximum rotation attained during the loading history, θ_u is the ultimate rotation capacity of the section, θ_r is the recoverable rotation when unloading, M_y is the yield moment and E_h is the dissipated energy in he section:

$$DI_{storey} = \sum (\lambda_i)_{component} (DI_i)_{component}; (\lambda_i)_{component} = \left(\frac{E_i}{\sum E_i} \right)_{component}, \tag{3}$$

$$DI_{overall} = \sum (\lambda_i)_{storey} (DI_i)_{storey}; (\lambda_i)_{storey} = \left(\frac{E_i}{\sum E_i} \right)_{storey}, \tag{4}$$

where λ_i is the energy weighting factor and E_i is the total absorbed energy by the component or storey i. The Park–Ang damage index calibration is shown in Table 2 (Park *et al.*, 1987a).

Pushover analyses are utilized in the IDARC program to track seismic behaviour and response of RC structures step by step. In each step, the fundamental period and damage rate of frames are extracted, and a new pattern is presented for damage assessment. This pattern is more reliable because it leans to the fundamental period, which shows the actual seismic behaviour of buildings that is caused by their configuration and their quality of construction, dissipated energy and deformation of

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Table 2. Interpretation of overall damage index.

Damage degree	Physical appearance	Damage index	State of building
Collapse	Partial or total collapse of building	>1·0	Loss of building
Severe	Extensive crashing of concrete; disclosure of buckled reinforcement	0·4–1·0	Beyond repair
Moderate	Extensive large cracks; spalling of concrete in weaker elements	<0·4	Repairable
Minor	Minor cracks; partial crushing of concrete in columns	–	–
Slight	Sporadic occurrence of cracking	–	–

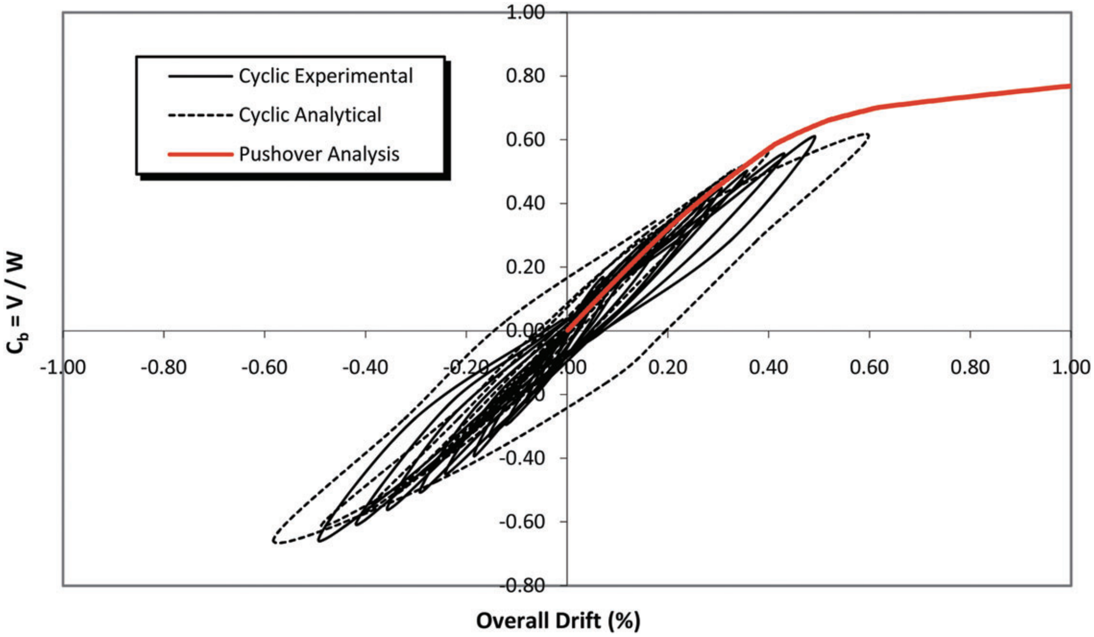

Figure 1. Comparison of analytical and experimental extracted data.

elements, which reflect the actual seismic behaviour of buildings that is caused by all of their elements individually.

2. VERIFICATION OF ANALYSES

In every analytical program, it is crucial that analysis at least reasonably reflects the behaviour of simple structures. Therefore, it is necessary to be sure about the program that extracted the data. In this regard, a comparison between analytical extracted data and experimental extracted data is done (Massumi, 2004). The result that is shown in Figure 1 is acceptable for engineering scale. The small disparity in the data is caused by experimental error in the laboratory and simplifier assumption in numerical analysis.

3. PURSUIT OF THE STEPS IN THE ANALYSES

This stage does not mean that seismic assessment of existing RC buildings based on fundamental period elongation need to modelling and analysis. In this stage, the correlation between damage rate and variation percentage of nonlinear fundamental period has been identified step by step. Six flexural

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RC frames, which are compatible with the third edition of the Iranian Code of Practice for Seismic Resistant Design of Buildings (Building and Housing Research Center, 2005) and Iranian National Building Codes (Part 9: Design and construction of reinforced concrete buildings) (Ministry of Housing and Urban Development, 2005), have been studied.

The configuration of the frames, which are 3 m high and 4 m wide, is shown in Figure 2. Most software cannot identify the location of plastic hinges. Therefore, the location of plastic hinges and their attributes are determined by users. Nevertheless, IDARC can identify the location of the plastic hinges (spread plasticity) according to the capacity of the elements.

The input hysteretic behaviour of elements has an essential role in the overall seismic behaviour of structures in analytical modelling. If inappropriate hysteretic curves are selected as elements of a structure, the final results of analytical modelling would be unrealistic. In this research, a multi-linear hysteretic model is selected for beams and columns, which is compatible with experimental extracted data in the laboratory to reflect an actual seismic behaviour of structure (Massumi, 1997).

In this analytical process, pushover analysis is carried out, and its results are shown in Figure 3. Assessment shows that the fundamental period is elongated in each step (with increase in base shear coefficient) according to the damage rate (Park–Ang index). Also, some of these steps are shown in Figure 4 for a 10-storey frame (δ is the fundamental period elongation). This procedure continues until the fundamental period abruptly shifts. This correlation is shown for each frame in Figure 5.

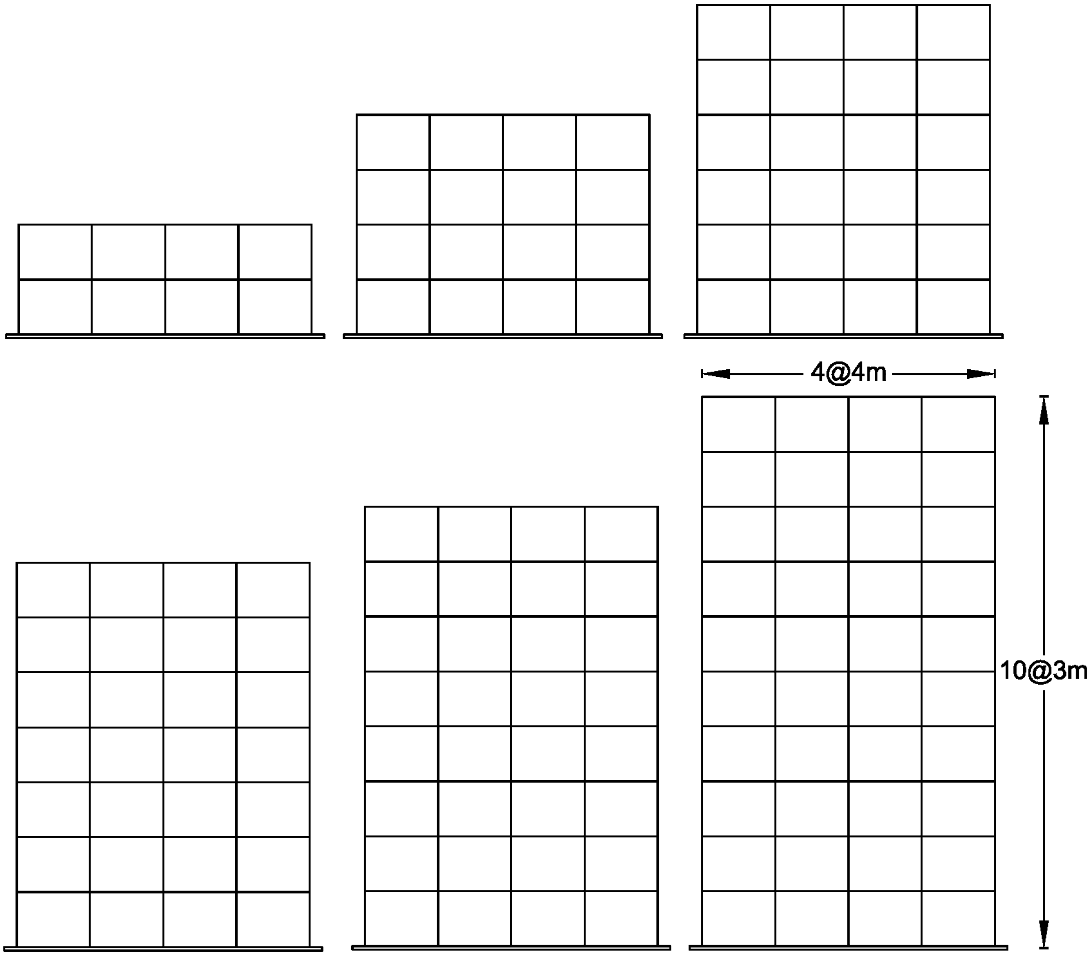

Figure 2. Frames' configuration.

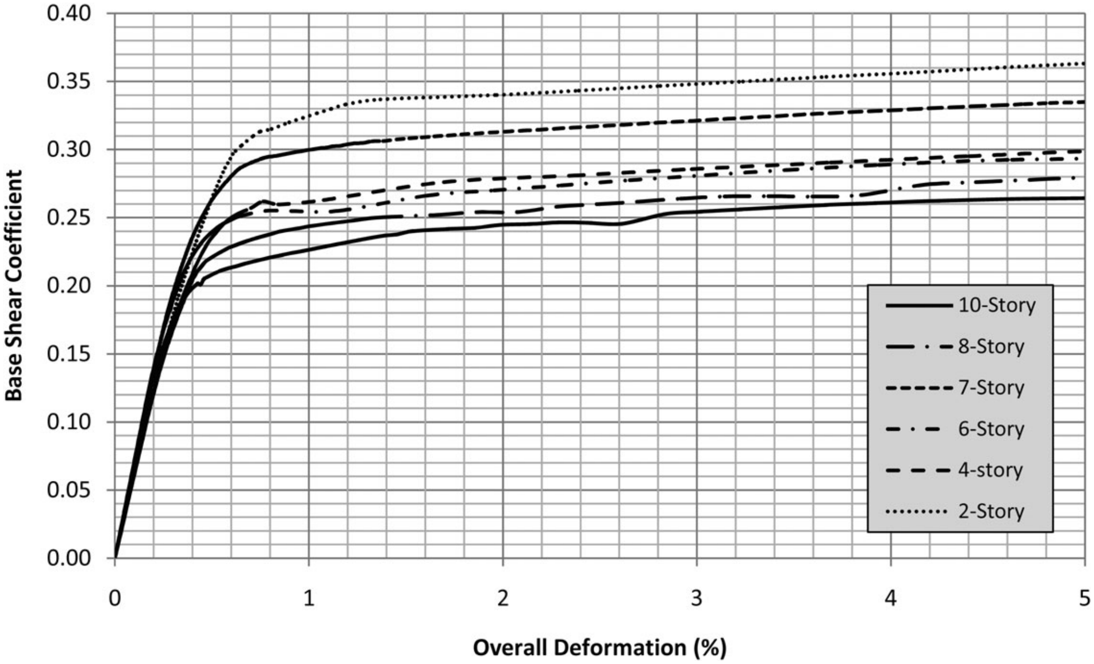

Figure 3. Capacity curves of reinforced concrete moment resisting frames.

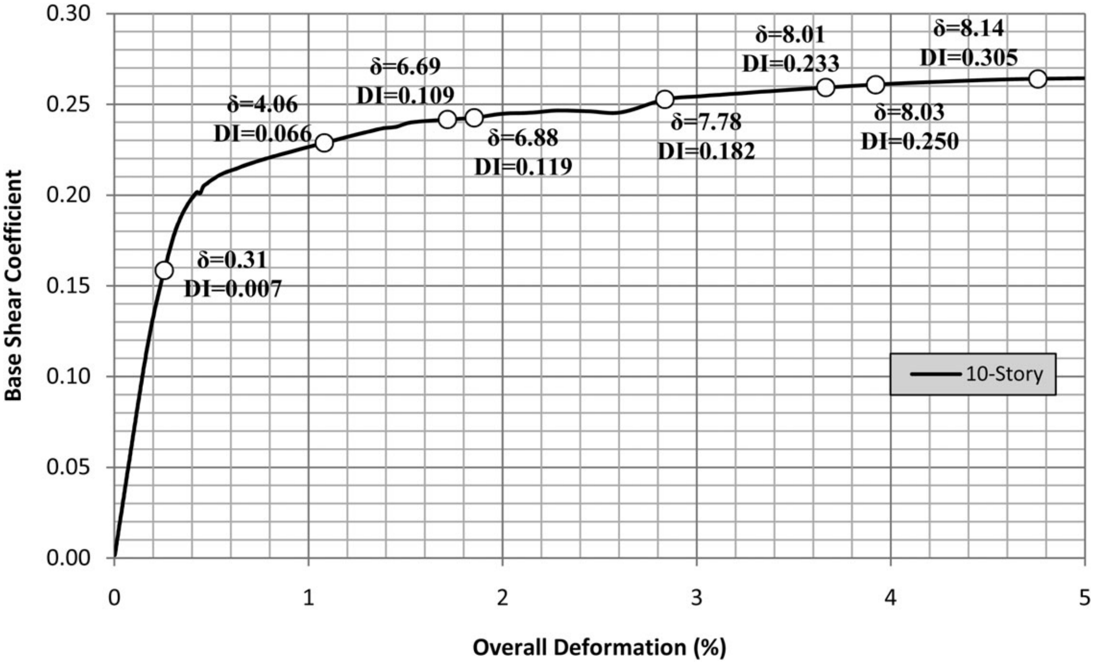

Figure 4. Fundamental period elongation corresponding to the damage rate.

4. DAMAGE PATTERN DETECTION

It is common that structures encounter softening (period elongation) when damage increases. Assessments in each step show that after a specific step, structures encounter severe softening and become irreparable; therefore they are unreliable. They are considered a repairable structure by assessments

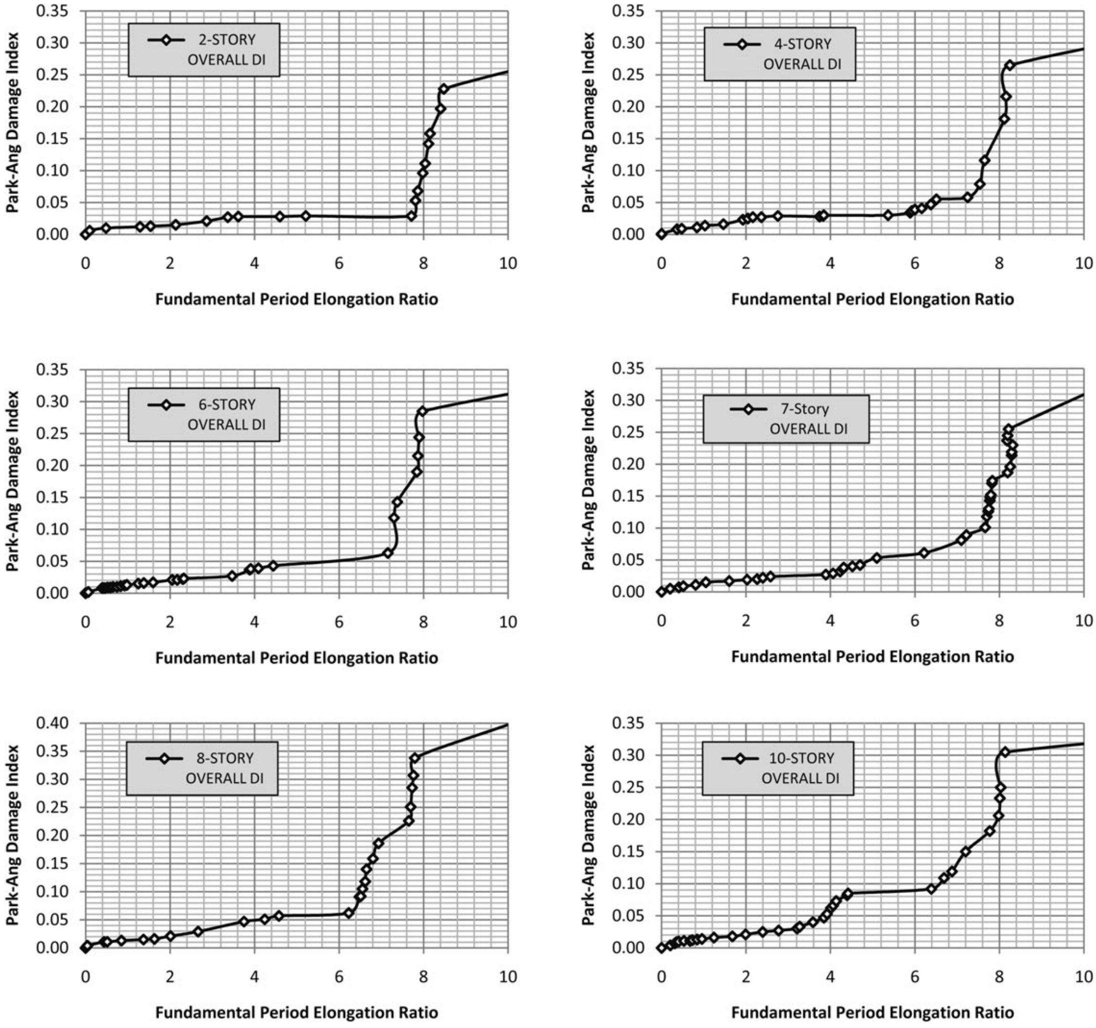

Figure 5. Period elongation pursuit corresponding to the damage rate.

merely based on deformation and dissipated energy of elements (Park *et al.*, 1987a). Consideration of fundamental period causes this disparity.

The seismic behaviour of structures originates not only in the hysteretic behaviour of elements but also in the configuration of structure and distribution of damage in the structure. Thus, if only the hysteretic behaviour of elements is considered in the damage model, it would not seem a precise damage model. In this regard, fundamental period would contribute to a complete damage model besides the hysteretic behaviour of elements.

Existing RC structures would be considered repairable in a new pattern if the fundamental period elongation is less than $\delta_{Critical}$ because after this stage, structures encounter severe softening. That the damage curves have an asymptote near the percentage of critical elongation is noticeable in Figures 6–11. This means that the stiffness of a structure tends to the least value. The damage pattern of structures that are analysed based on the percentage of period elongation are shown in these figures. Steps that pertain to severe softening are eliminated from the analysis process because this new pattern is valuable while the structures are repairable.

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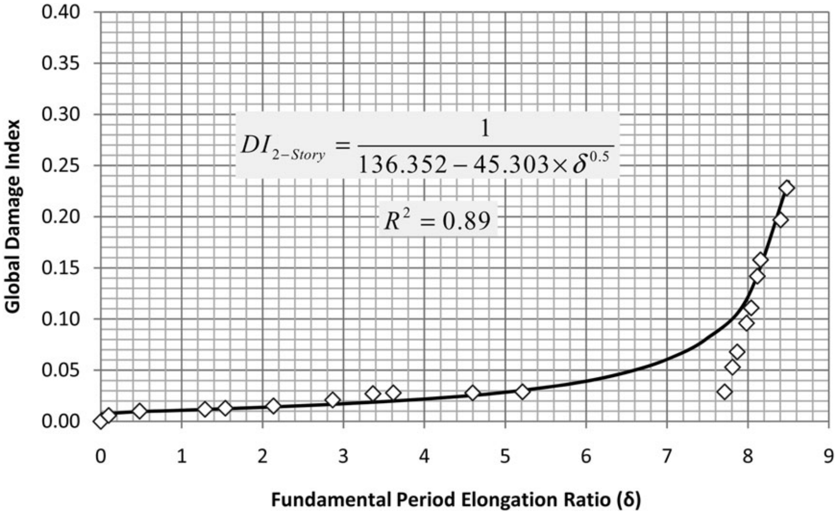

Figure 6. Two-storey damage pattern.

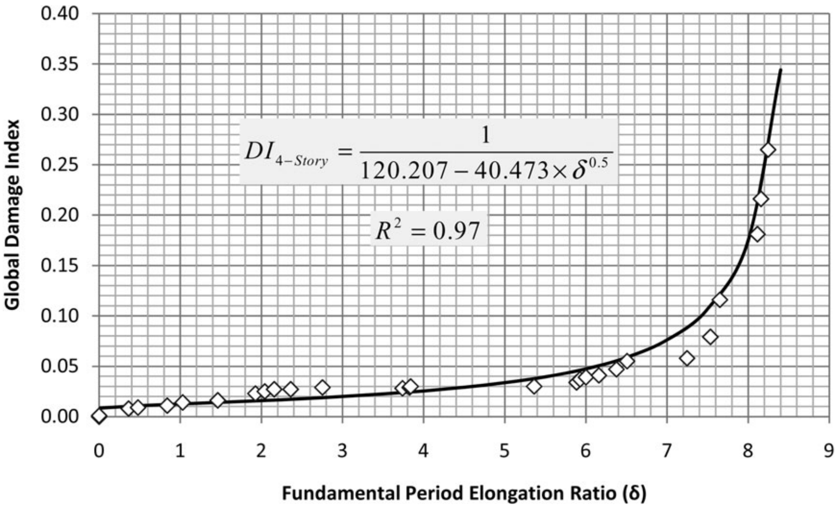

Figure 7. Four-storey damage pattern.

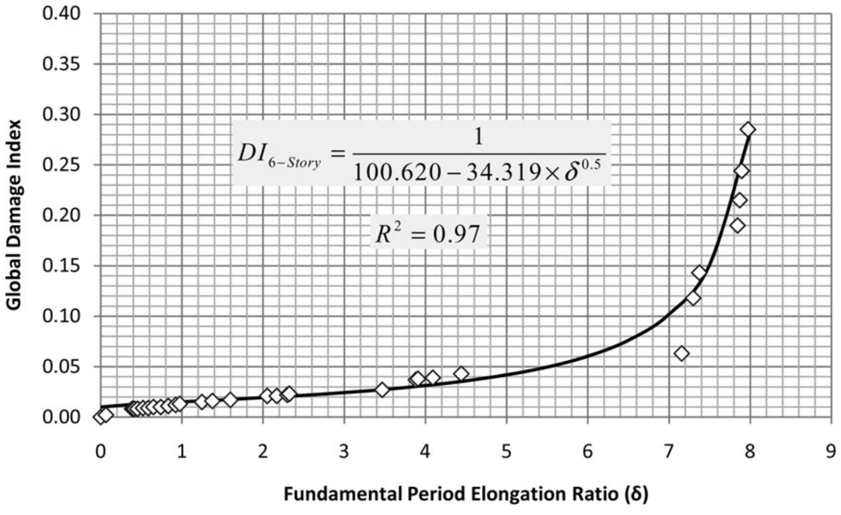

Figure 8. Six-storey damage pattern.

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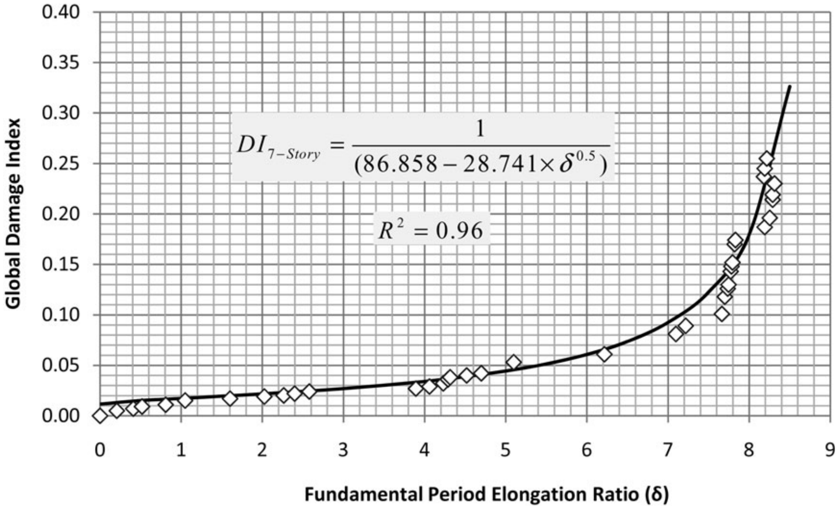

Figure 9. Seven-storey damage pattern.

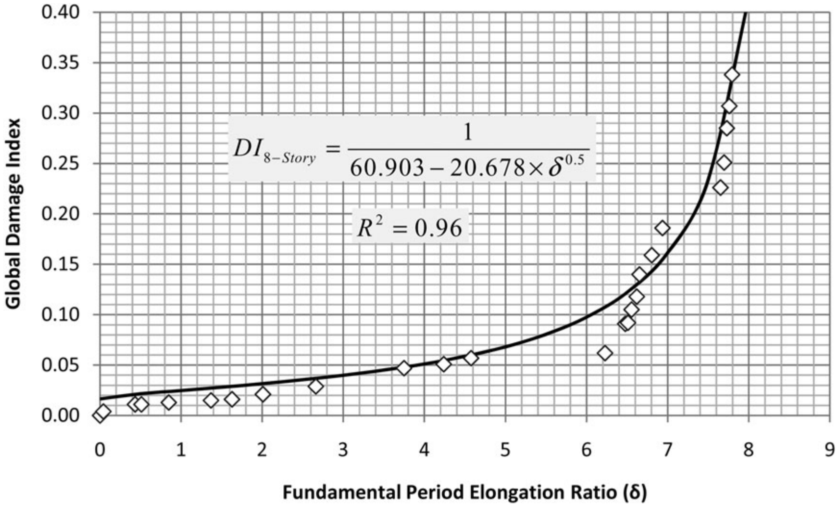

Figure 10. Eight-storey damage pattern.

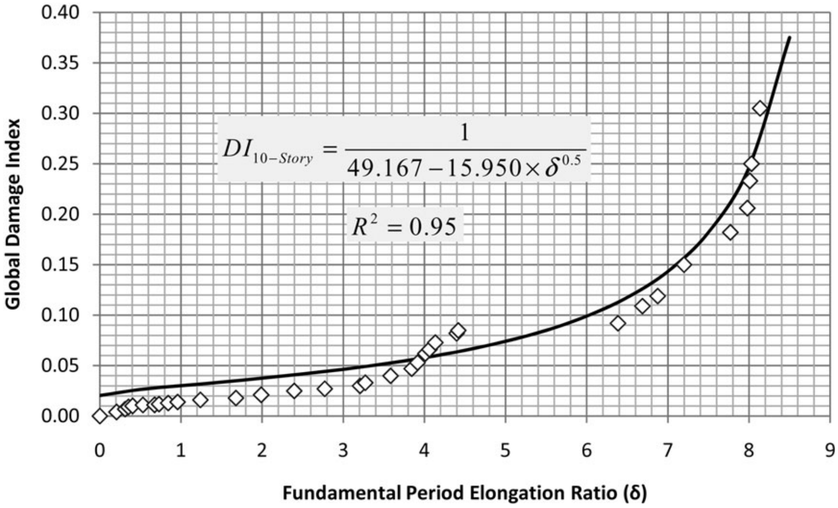

Figure 11. Ten-storey damage pattern.

5. PROPOSED DAMAGE PATTERN

A general damage pattern is proposed as a consequence of seismic damage assessment of these flexural RC frames (with no shear wall). This pattern is based on the percentage of nonlinear fundamental period elongation (δ), which is calculated by Equation (5). $T_{plastic}$ is the period of existing damaged RC buildings, which is extracted by field tests. $T_{elastic}$ is the initial period when they are not damaged by an earthquake and is calculated by experimental formulas such as the Iranian Code of Practice for Seismic Resistant Design of Buildings (3rd edition) (Building and Housing Research Center, 2005) suggests in Equation (6). Also, H is the height of the RC frames in meters:

$$\delta = \frac{(T_{plastic} - T_{elastic})}{T_{elastic}}, \tag{5}$$

$$T_{elastic} = 0{\cdot}07H^{\left(\frac{3}{4}\right)}. \tag{6}$$

A new damage pattern is proposed in Equation (7). α and β are damage coefficients that pertain to the initial elastic period of frames that is calculated by experimental formula. The correlation curves of damage coefficients with initial elastic period are presented in Figures 12 and 13:

$$DI = \frac{1}{\alpha - \beta\delta^{0{\cdot}5}}. \tag{7}$$

The following are the steps to seismic damage assessment of existing RC buildings based on new damage pattern:

(a) Extract the fundamental plastic period of existing damaged RC buildings by field tests (Moshtagh and Massumi, 2009).
(b) Calculate the fundamental elastic period of existing damaged RC buildings by experimental or code period (usually for vital buildings this is available).
(c) Calculate δ and read damage coefficients from correlation curves.
(d) Utilize new pattern (new pattern is valuable while $\delta \leq \delta_{Critical}$).

$\delta_{Critical}$ is a new criteria in deciding whether the damaged building is repairable or not. A building would be repairable if its period elongation is less than $\delta_{Critical}$ because it will encounter sever softening afterwards. This softening occurs, whereas some elements are still capable of loading. This paradox originates from how the plastic hinges and cracks are distributed throughout the structure,

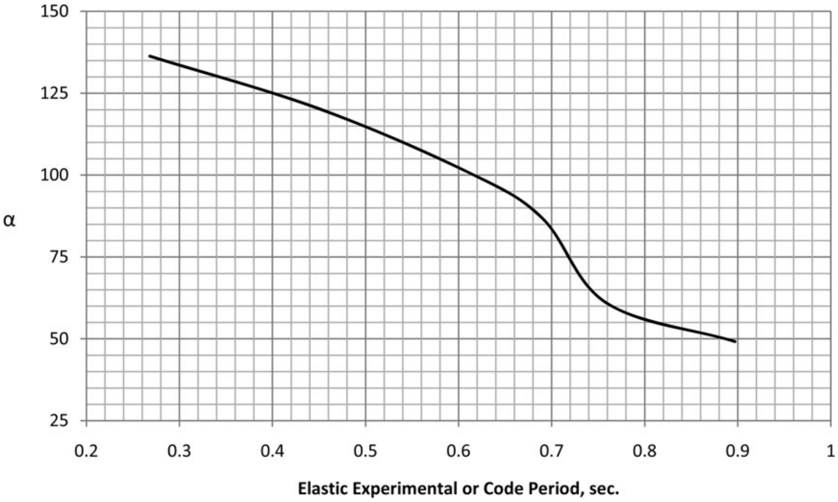

Figure 12. Damage coefficient value of α.

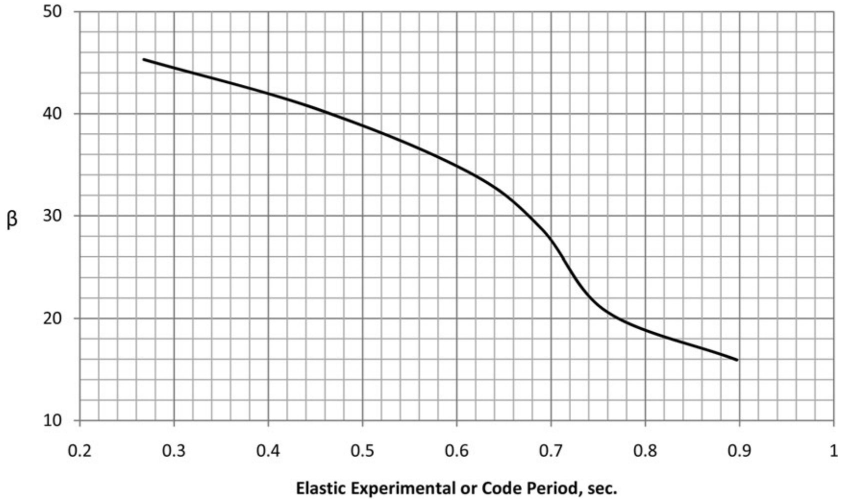

Figure 13. Damage coefficient value of β.

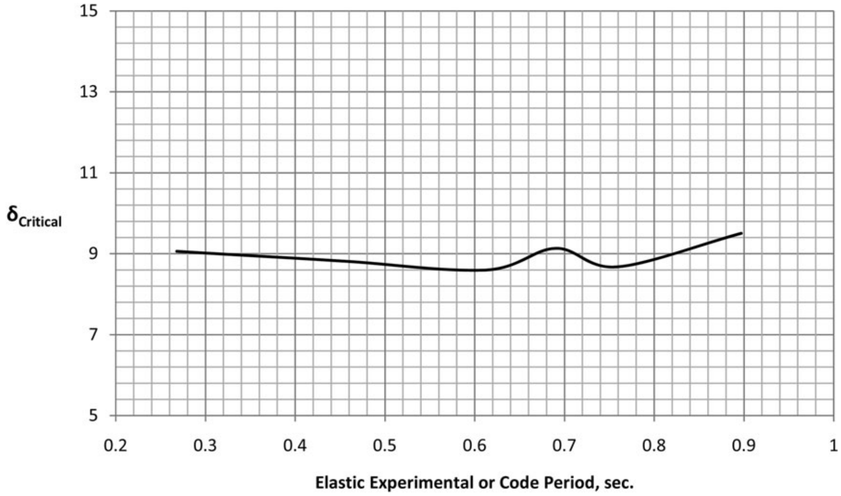

Figure 14. Value of $_{\delta}$Critical.

which causes the structure of the global stiffness matrix to change abruptly. The new damage pattern is represented in a new format by changing Equation (7) to Equation (8). The value of $\delta_{Critical}$ is related to the initial elastic period, which is correlated in Figure 14:

$$DI = \frac{1}{\beta(\delta_{Critical}^{0.5} - \delta^{0.5})}. \tag{8}$$

In this pattern, utilizing the elastic and plastic experimental period is emphasized. However, in some references that have empirically and analytically assessed many RC frames, the disparity in the experimental and analytical elastic periods is usually less than 100% (Massumi, 2004; Tasnimi and Massumi, 2006). The disparity in the experimental and analytical elastic periods for these five frames is represented in Table 3.

According to some references, the analytical elastic period could be utilized instead of the experimental elastic period in this new damage pattern because it does not lead to a large deviation. Therefore, this new pattern is also useful for buildings whose initial elastic periods are not available. It

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Table 3. Comparison of experimental and analytical elastic period.

Number of storeys	Analytical elastic period (s)	Experimental (code) elastic period (s)	Disparity (%)
2	0·52	0·27	94
4	0·69	0·45	53
6	0·77	0·61	26
7	0.83	0.69	20
8	0·92	0·76	21
10	0·96	0·90	7

should be further pointed out that the plastic period of damaged buildings should be just experimentally extracted by field tests.

6. CONCLUSION

The actual dynamic behaviour is affected by the dynamic behaviour of elements, configuration of structures and infill panels. Furthermore, the distribution of plastic hinges and cracks and also the damping ratio affect the dynamic behaviour when the structure is on nonlinear levels. The Park–Ang damage index considers the hysteretic behavior of each element, as well as possible dissipated energy and deformation. To complete this damage index and to assess the real damage situation under seismic loads, the fundamental period is considered, which reflects the effects of configuration, infill panels and distribution of damage. Fortunately, a logical pattern between period elongation and damage rate was detected in the pursuit of the steps in the analysis. Finally, it would be possible to cheaply and expeditiously obtain a precise seismic assessment of existing RC buildings by a new damage pattern even though there is no initial modal information on them.

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