Designing Reinforced Concrete Frames with Earthquake Damage Control

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Abstract: Controlling the amount of structural damage is one of the most important issues in new design methods such as performance-based design. The purpose of present research is to present a new design method with damage control for reinforced concrete bending frames. For this purpose, at first a static damage standard is developed and then suggested method is applied to design a 7 store frame. Then in order to assess suggested method accuracy, non-elastic damage analysis is performed on mentioned frame. The results show that suggested method is effective on designing reinforced concrete bending frames, with damage control.
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1. Introduction

Usually and traditionally, the main issue in earthquake design of structures is to preserve residents' life with the hope that structural damage after earthquake can be repaired. California earthquake in recent years showed that the amounts of structural damages in these earthquakes were unacceptable and cost needed for repairing structures were very high. Attempts to modify design methods and design regulations criteria finally resulted in developing new method named "performance-based design". The main subject in performance design category is to control the amounts of structural damages under earthquake. For this purpose, according to performance standards, a relation between introduced performance levels and the amounts of expected structural damages has been created [1]. Introduced performance levels in standards, include four levels which are usable level, immediate exploitation, life safety and preventing collapse respectively. [2, 3]

The potential damage of an earthquake on structures is one of the base discussions in earthquake engineering. A reliable scale of earthquakes damage potential can have many applications in new structures analysis and design and also present available buildings seismic assessment [4]. Earthquake parameters such as maximum acceleration and elastic response spectrum although are many important but can't provide reliable standards of an earthquake's damage potential. One way for measurement of the amount of structural damage is to use damage indices [5-9]. A damage index is stated based on combination of many structural deformations which cause damage and also the amount of damage which is caused because of cyclic loading repetition. Until now, different damage indices have been introduced but none of them are applicable widely. Another way to estimate degree of structural damage is to estimate the relation between damage and relative storey's movement. Relative storey's movement is one of the initial parameters in assessment of structure performance [10, 11] and has been broadly taken into consideration as a main parameter in measurement of buildings plastic deformations [12, 13]. Of course some researches show that this parameter is an unsuitable and insufficient standard in structural damage control. Since relative movement standard is an insufficient parameter a structure performance (or damage) control and on the other hand since damage index assessment include dynamic hysteresis energy calculation which is so time-consuming and a complicated process, so in this research an effective and applicable standard for estimation of reinforced concrete bending frames and by using of push over Analysis results is developed. The main purpose of this research is development and extension of a new method for designing reinforced concrete bending frames, with damage control, based on this research suggested damage standard. For this purpose, initially functions for estimation of structural damage are obtained by using of push over analysis and then suggested method is used for designing a 7 story reinforced concrete frame under 7 earthquake records. Then, in order to assess suggested method accuracy, non-elastic damage analysis is done. Results show that suggested method can be very efficient and applicable in designing reinforced concrete bending frames, with damage control.

2. Dynamic Damage Index

In this research the amount of structural damage in dynamic analysis is calculated by using of Park and any damage index. These researchers' suggested index is a compound index based on deformation and wasted energy amount in the structure [7]. These researchers have calibrated their suggested damage index by observing physical damage on several samples. Appropriateness of real damage to index values suggested by these researchers has been presented in table 1.

Table 1- Details of Damage Proportionate to Park and Ang index

Damage degree	External appearance	Damage index	Building situation
Collapse	Appearance or total collapse of building	>1	Demolished
Intense	Concrete wide crushing, appearing ricochet amateurs	0.4-1.0	Can't be repaired
Moderate	Large and extensive cracks, concrete delaminate in weaker members	0.25-0.4	Repairable
Little	Small cracks, local crushing of concrete in columns	0.1-0.25	Repairable
Slight	Appearing sporadic cracks	<0.1	Repairable

This index value is equal to 0 when structure remains elastic (i.e. it hasn't happened any damage) and will be equal to when it happen so damages that structure has potential to break. Other performance states such as immediate exploitation and life safety and so on are defined by consideration of a range between 0 and 1. In order to determine Park index range corresponding to performance levels, by refer to performance standards such as ATC40 [16] and FEMA273 [2] and also table 1, we can correspond usable performance levels, immediate exploitation, life safety and collapse prevention to damage degrees of without damage (slight), little damage, moderate damage and severe damage of Park index respectively.

3. Static Damage Index

In this research energy damage index has been suggested in order to measure the amount of structural damage by using of push over analysis results. Using wasted energy by structure, has been applied in many researches in order to determine the amount of structural damage most of which have been based on dynamic analysis. Kato and Akiama took into consideration the wasted accumulated energy by hysteresis attenuation as an acceptable index for estimation of structural damage [17]. Zhang et al. used input energy and structure plastic energy for determining structural damage [18] and so on. Referring to energy balance equation for none-linear system, under earthquake:

Equation (1, 2)

Or

KE+DE+SE+PE=IE

In which KE is kinetic energy, DE is attenuation energy, SE is strain energy, PE is plastic energy and IE is the energy into the system. As you can see, the energy into the system is wasted through 4 mechanisms. In general stare, kinetic and strain mechanisms undertake little portion of the amount of energy wasted by structure and main amount of energy is wasted by attenuation and yield energy. In these two mechanisms also the more structure enters non-linear phase, portion of yield energy is more than attenuation energy which indicates non-elastic mechanisms are slower than elastic systems. The purpose of this section is to provide an index based on energy absorbed by structure in push over analysis. Since, capacity curve resulted from push over analysis is structure Hysteresis push-rings, then we can say that the area below the curve in performance point, introduces energy absorbed by structure in its largest Hysteresis ring under certain earthquake which often has great portion of energy absorbed by structure. This index is calculated by following relationship:

Equation (3)

In which E_{pp} is the area below capacity curve in performance point, E_{ip} is the area below capacity curve in a point corresponding to entering structure into non-linear phase and E_{fp} is the area below capacity curve in a point corresponding to section final capacity which are explained then. In order to calculate E_{pp} area, at first is calculated by using of numerical integration methods of area below capacity curve in performance point and then with respect to existing relations in ATC40 [2] yield point is determined. Afterwards, using below relationship, which is available in reference [2], concerning ¼ of structure Hysteresis ring is calculated:

Equation (4)

In which d_p and a_p are yield point coordinates and d_y and a_y are coordinates of performance point. In definition of this index, the primary point which is entry of structure to non-linear phase and is considered as beginning of structural damage, a point of capacity curve has been considered correspond to the first crack of structural members and damage index value in this point is equal to 0 and the more structural behavior enter non-linear, structural elements are more damaged and this index value will be more, until eventually in structure final capacity point, value of this index will become 1. In order to determine structure final capacity various definitions have been propounded, but in this research, the structure final capacity point is considered a point form structure capacity curve in which by slight increase in lateral force, structure encounter a very large sudden deformation compared to the previous step and in other words jump occur in structure capacity curve. Steps for calculating E_{fp} also is similar to E_{pp}. E_{ip} is area below capacity curve in first crack point. It should be noted that hereafter this index will be named energy damage index.

4. Designing Frames

In this section in order to assess damage indices introduced in previous sections, 14 reinforced concrete frames were considered so that include a large number of storeys and spans [15]. Four-span frames include 5, 8, 12, 15 storeys, five-span frames include 4, 6, 2, 8 and 10 storeys and two-span frames include 1, 3, 5, 7 and 9 storeys. The height of all storeys were equal to 3.2 and length of spans also were equal to 4 m. when modeling these frames it's assumed that all frames are placed in stone beds and have been loaded for region with moderate risk according to standard 2800 and designed according to ABA regulations (In designing these frames, all criteria such as lateral deformation restriction in regulations 2800 has been considered). Frames have 4 m loader width and in all storeys have dead load of 760 kg/2m and live load of 200 kg/m^2. According to standard, importance of frames has been assumed moderately 2800. In process of analysis and design of these frames, characteristic strength of concrete has been assumed equal to 30 Mp, concrete elasticity modules 27386 Mp, strain correspond to maximum strength of concrete 0.002, concrete final strain 0.003, flow resistance of steel 300 Mp and elasticity modules of steel has been assumed 200000 Mp.

5. Earthquakes Calibration

In this research, 7 earthquake records from records set available in FEMA440 [19] had distance from fault and were selected proportionate to geotechnical properties of stone bed and measured according to 2800 regulations criteria so that spectrum of average obtained from them in range of 0.03 to 2.4 s (which based on regulations 2800 [17] is important range for frames designed in this research (the range between 0.2T and 1.5T)) has minimum difference with 1.4 times of spectrum of regulation 2800. Properties concerned with these records and average spectrum obtained from them is available in reference [20].

6. Damage Analysis

The purpose of this section is measurement of energy damage index. For this purpose, after structures' modeling, push over and non-linear dynamic analyses were performed on them and energy damage index values in push over analysis and Park damage index values in dynamic analysis were calculated. In order to calculate damage indices in push over analysis initially structure performance point should be determined and then these indices values should be calculated in structure performance point. In order to determine performance points, capacity spectrum method according to descriptions presented in reference [21] has been used. Afterwards, in order to determine the relation between stated indices, 5 performance points were calculated for each frame which were related to records average response spectrum and spectrums which are 1.5, 2, 2.5 and 3 times this spectrum respectively. Then damage indices values in these points were calculated and after that in order to calculate damage indices in dynamic state, for each spectrum, existing records were converted to criterion and nonlinear dynamic analysis of frames were done and according to each calculated damage in performance points in push over analysis, by averaging results related to 7 selected earthquakes, damage related to non-linear dynamic analysis were calculated, which concerned results will be presented. It's notable that in figure 1, triangle shaped points are relevant to damage correspond to average spectrum and correspond to designed earthquake of regulations 2800 and circle-shaped points are correspond to 1.5 times average spectrum, which approximately can be correspond to risk level M.E. in ATC40, which indicates 5% contingency during 50 years. Thus in order to conservative estimation of damages at this level, the maximum limit for this estimation i.e. 1.5 times average spectrum has been selected) and other points have been specified by rhombic. Hereafter in this research we mention these points by naming the shape.

7. The Relationship between Indices

In this section, we have compared values of Park and Ang damage index in dynamic analysis to values of energy damage index which have been calculated in performance points according to section 3. As you can see in figure 1, at the beginning of this chart, Park and Ang damage index values are higher and as we move toward the end of chart, this difference is reduced and by referring to presented descriptions in section 3 we can say that this issue is because of increasing Hysteresis energy share of wasted energy by structure and more entrance of structure into non-linear phase. Moreover, the energy damage index values average is 0.4 which is very close to Park damage index average. Other notable material in this chart is that energy damage index variations range for circle-shaped and triangle-shaped points is 0.027 to 0.176 and 0.11 to 0.36. As you can observe in figure 1, presented energy damage index in this research, has scattering points proportional to

Park and Ang damage index in dynamic analysis and since this index is general and has simple calculation steps, so using it in recognition of structural damage can be very effective. In order to increase the accuracy in presented relationships between these indices, there have been specified various ranges of damage which respectively are little damage range (dynamic damage: 0-0.26), moderate damage (Dynamic damage: 0.26-0.52) and intense damage range (dynamic damage: 0.52-1.0). In each of these ranges, by interpolation between these index values, relations have been presented as follows by using of which we can obtain Park damage index values from results of push over analysis and energy damage index values (for little to intense damage ranges respectively):

(5) $DI_s = 0.255DI_D + 0.052$

(6) $DI_S = 1.237DI_D - 0.187$

(7) $DI_S = 1.8DI_D - 0.448$

Which in these relations, DI_D is Park damage index in dynamic analysis and DI_S is static damage index in push over analysis. Although by using of equations 5 to 7 we can calculate Park index values with good accuracy, but since the purpose of designing is to provide a safe pattern, so equations 8 to 10, which are related to conservative pattern in little to intense damage ranges, is presented as follows:

(8) $DI_S = 0.255DI_D + 0.05$

(9) $DI_S = 1.237DI_D - 0.292$

(10) $DI_S = 1.8DI_D - 0.62$

8. Suggested Design Method

In this research suggested method, it's considered that the structure which has been designed based on traditional methods for regulations design spectrum should be able to tolerate a more intense earthquake so that the amount of damage on that structure can be controlled. For this purpose, initially the structure typically is designed for regulations design spectrum and then energy damage index value for a more intense spectrum is calculated by performing push over analysis and by using of presented equations, its corresponding Park index value is calculated. After that, calculated damage value is compared to range considered by designer. Now, if damage is more than expected range, then structure should be strengthened and again static damage be calculated and again be compared to considered range. These try and error operations should be repeated so that finally designer's viewpoint about damage is met. The important point is that what members should be strengthened. For this purpose and in order to achieve acceptable pattern by spending minimum cost, in each repetition, on structure performance point the amount of wasted energy in structure various members is calculated and members which have absorbed most energy, are selected for strengthening. It's notable that in each damage range, 3 lines have been provided which equations 5 to 7 are related to acceptable pattern with minimum safety and equations 8 to 10 are related to very conservative pattern and design band between these lines can be considered in design. By more approaching equations 8 to 10, safety becomes more. Thus a pattern is considered acceptable when its calculated damage is in range of values obtained from equations of optimized pattern and conservative pattern.

9. Application of Suggested Design Method for a storeys Frame

In this section a 7-storeys and 3-spans reinforced bending frame is designed. This design example is different from frames considered to develop indices relations in section 7. This frame initially is designed based on spectrum of standard design 2800 and then is controlled for considered damage level. Considered properties for designing is according to section 4. Lateral load distribution is proportionate to exponential distribution, according to FEMA273. Strengthened spectrum is considered 1.3 times average spectrum (figure 2) (This spectrum is described more in section 10). The amount of dynamic damage is 0.4 which corresponds to live safety upper bound (according to table 1). This damage bound is placed in average damage range in figure 1 and thus equations 6 and 9 are used in order to determine acceptable damage index values corresponding to this dynamic damage. By replacing 0.4 in these equations static damage range will be 0.2 to 0.31. by performing push over analysis and calculating energy damage index, it's observed that energy index value is obtain 0.378 which is out of acceptable range and indicates that initial design is unacceptable for live safety damage level against strengthened spectrum. After that, by strengthening some members which have absorbed more energy, by increasing studs and repeating try and error three times, finally the amount of static damage was reduced to 0.26 which is placed in acceptable range. Spectrum and capacity and performance points of initial pattern and final pattern have been shown in figure 3.

10. Assessment of Suggested Method

In this section in order to assess effectiveness of suggested method, non-linear dynamic analysis is performed on mentioned frame. For this purpose, 7 earthquake records which properties have been listed in table 2, has been considered. These records have been considered so that their spectrum is placed in minimum distance from spectrum of standard design 2800. Average spectrum of these earthquakes, standard 2800 spectrum and strengthened spectrum of them have been shown in figure 2. After that, non-linear dynamic analysis was performed for records corresponding to average spectrum on initial structure (not-strengthened) and Park damage index values were calculated and finally damage average of these earthquakes was obtained 0.48 which was out of acceptable dynamic damage i.e. less than 0.4. Then by performing similar procedure for final frame (strengthened) by using of records corresponding to strengthened spectrum (1.3 times average spectrum) again damage average for these earthquakes was obtain 0.346 (damage values of each of earthquakes in these two analysis, have been shown in figure 4).with respect to results, it's observed that initial structure against strengthened spectrum hasn't had desirable performance for live safety level and the amount of its damage has been more than acceptable value, but strengthened structure by using of research suggested method, has suitable amount of damage and by comparison between its amount of damage and bound dynamic damage value (0.4) it's observed that there is about 13% difference which indicates that suggested method has significant effect on assessment and anticipation of the amount of structural damage.

Table 2: Properties of selected earthquakes

Earthquake number	Record	Station	Component (deg)	PGA(g)
1	Loma Prieta	58151	90	0.092
2	Loma Prieta	58151	0	0.078
3	Loma Prieta	58539	205	0.105
4	Landers	21081	0	0.115
5	Landers	21081	90	0.146
6	Santa Barbara	283	222	0.203
7	Northrid ge	90019	180	0.256

11. Conclusion

In this research a new suggested method for designing reinforced concrete bending frames, with damage control, was developed by using of which we can place damage in designer considered range. To provide this method, a static damage standard was developed based on energy concept. The results of comparison between suggested damage index and Park index in non-linear dynamic analysis showed that introduced index scattering is proportionate to Park index. Then, in order to design structures a band named "design band" was considered. Eventually, suggested design method was used to design a 7-storeys 3-spans frame and results obtained from assessment of this standard through performing non-linear dynamic analysis showed that suggested method has desirable quality.

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