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Assessing the Effect of Deformation and Energy Damage Indices in Seismic Vulnerability of Steel Moment- Resisting Frames

***Kourosh Mehdizadeh* [1*], *Abbasali Sadeghi* [2], *Seyede Vahide Hashemi* [3], *Mina Mahdizadeh* [4]**

[1*] *Department of Civil Engineering, Garmsar Branch, Islamic Azad University, Garmsar, Iran*

(ko_ma751@mail.um.ac.ir)

[2] *Department of Civil Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran*

[3] *Department of Civil Engineering, University of Sistan and Baluchestan, Zahedan, Iran*

[4] *Department of Civil Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran*

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ABSTRACT

In evaluating the degree of structural damages after a destructive event like an earthquake, the assessment of damages in different points of the structure is very important. Thus, it becomes necessary to introduce some indices to assess the seismic damages in the structural elements. The deformations and amount of dissipated energy of earthquake by the elements are usually considered in defining damage indices. Some damage functions take only one of the above-mentioned parameters and some others might consider the associated effect of deformation and amount of energy dissipation of elements. In this paper, after designing steel moment resisting frames with 4, 7, 10, 15, 20, and 25 story with considering 3 and 5 bays, they are modeled in OpenSees software in order to investigate the performance of steel moment-resisting frames under seismic excitations by using deformation, energy, and Park-Ang damage indices. The values of damage indices have been calculated on the basis of nonlinear dynamic time history analysis under 4 near-fault ground motion records. The results revealed more effective role of deformation than dissipated energy and combined parameters in quantitative expression of seismic damages.

Keywords:

Damage index, Deformation, Dissipated energy, Park-Ang, Nonlinear dynamic time history analysis, Near-fault ground motion.

1. Introduction

Even though standard design approaches based on the concept of the force reduction factor are recognised in the seismic design of steel and reinforced concrete (RC) structures, they do not result in structures with uniform and rationally defined safety and performance criteria [1-4]. As a result, researchers have paid more attention to damage indices or damage indicators. A damage index is a state variable that links a particular damage situation induced by complex nonlinear deformation, energy dissipation, or low-cycle fatigue to a single point on the monotonic backbone curve. Because a damage index is only a normalized damage indicator, the two definitions are identical in this context. Over the last 20–30 years, a substantial amount of research has been conducted on the development of damage indices. In general, structural damage has been classed as either economic or connected to safety/strength. Economic damage indices are often expressed as a ratio of repair to replacement costs for an entire structure or a single structural component. The reduction of structural resistance is typically associated with safety/strength damage indices. The earthquake engineering community recognizes the need to enhance current seismic rules and design methodologies in light of prior building disasters. Part of this might be attributed to muddled design approaches like as the equivalent static force procedure, which ignores the cyclic load effect that happens regularly during earthquakes. On the other hand, cyclic loading has long been recognized as having a significant impact on the accumulated damage to structures. This flaw can be remedied by employing a more appropriate technique of assessing seismic damage, such as a damage index that takes into account maximal deformation as well as inelastic energy dissipation. On the one hand, an earthquake is one of the world's most complicated natural events, and forecasting how structures would behave in earthquakes is exceedingly challenging. Many decades of effort have been and continue to be done in this direction. To reduce the rate of damage following an earthquake, each component of the building must be inspected and analyzed independently. On the other hand, an earthquake is one of the most complicated natural events in the world, and it is extremely difficult to forecast how structures would behave in earthquakes. Many efforts have been made and continue to be made in this direction dating back decades. To lower the damage rate after an earthquake, each component of the building must be independently analyzed and evaluated. A numerical value that is a function of structural features and external loadings, according to the researchers, can be used to identify the state of a damaged member or structure [5]. In recent decades, many methods for anticipating seismic damage have been developed. As a result, considerable effort has been expended to improve current earthquake resistant design approaches in order to not only avoid collapse in the event of a destructive earthquake, but also to limit damage in the event of a minor earthquake. Furthermore, multi-level probabilistic structural performance requirements are offered as an improvement over the standard force strength technique in the new design philosophy. Putting all of these new ideas into action, however, needs the development of a qualitative damage index and measure. The notions of local and global damages, as well as structural vulnerability, play important roles in seismic design of structures. Damage indices could be used to express structural damage. Damage indices are often displayed with values ranging from "zero" to "one." The number "zero" denotes no damage, while "one" denotes the collapse of an element or structure. Furthermore, the damages ranging from low to high rate are assessed using values ranging from zero to one. Damage indices could be used to express structural damage. Meanwhile, structural deficiencies and insufficient ductility may be to blame for the fragility of many existing structures. Incomplete load paths, strength and stiffness discontinuities, plan and height abnormalities, weak column/strong beam, and other eccentricities are common structural system flaws. Insufficient shear reinforcement, inadequate confinement, and insufficient anchorages and other detailing are characteristics of low ductility detailing. An index might reflect the state of damage of a component, a story, or the entire system. The damage index is used as an indicator to describe the state of existing structures' lateral load-carrying capacity and reserve capacity. As a result, research into the damage index and its availability is required. As local damage indices, several damage indices are calculated for each component of the building. The component damage indices can be combined using a weighting process to obtain the structure's global damage index. These damage indices were developed utilizing structural reaction parameters obtained through analytical evaluation of structural response. Ductility ratio, inter-story drift, slope ratio, maximum drift, flexural damage ratio, low cycle fatigue, final softening index, and Park-Ang index are examples of response-based damage indices. Damage indices like inter-story drift and maximum drift are vital and necessary for describing displacement or deformation [6]. In this study, Steel moment-resisting frames with 4, 7, 10, 15, 20, and 25-story and 3 and 5 bays are considered and then modelled in OpenSees software [7] to explore the performance of steel moment-resisting frames under seismic excitations using deformation, energy, and Park-Ang damage indices. Following that, a nonlinear dynamic time history analysis is performed, and the damages of the aforementioned frames are quantified.

2. Background of Damage Index

A damage index is designed for the seismic damage assessment of the structures in order to measure numerically the degree of damage. Damage indices can be used to quantify damage and link it to costs and other consequences, such as potential risk following an earthquake. As a result, in earthquake-prone areas, the damage index might be critical in retrofit decision-making and disaster preparation.

There are three types of structural responses utilized as damage parameters:

1. Plastic deformation causes elements or structures to deform.

2. Energy dissipation in the elements due to hysteretic behavior: Prior to breakdown, structural elements have a limited capacity to dissipate energy cyclically. The amount of energy dissipated is a good estimate of how much harm was done during loading.

3. Changes in the dynamic features of the structure, such as the structure's first natural period.

Damage indices are frequently standardized to have a value of zero when there is no damage and a value of unity when there is complete collapse or failure. A damage parameter, on the other hand, is a monetary value used to estimate damage.

Damage indices based on strength are simple to calculate and do not require a structural response analysis. They are based on geometric qualities of structural elements such as beams, columns, braces, and steel and reinforced concrete shear walls, as well as material attributes. These types of damage indices should be calibrated against observed damage utilizing a large real-world database or the results of non-reliance structural analysis.

Shiga et al. (1968) [8] and Yang (1980) [9] were the first to propose a strength-based damage index. The damage evaluation approach based on structural response necessitates a thorough investigation, as well as sufficient data to calibrate the results. This technique demands exact information on structural models, materials, and site-compatible ground motion descriptions [10]. Figure 1 depicts the classification of seismic damage indices in structures.

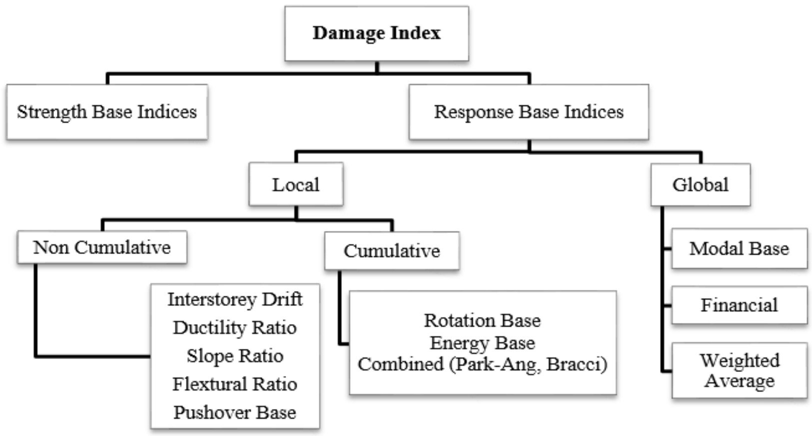

Figure 1. Classification of damage indices [11].

Whitman (1972) calculated the earthquake-induced damage index by comparing the cost of repair to the cost of rebuilding in different degrees of ground motion [12]. Okada et al. (1974) proposed a method for calculating the seismic safety of reinforced concrete structures [13]. Stephens and Yao (1975) [14] also proposed a damage index based on relative displacement. Bertero and Bresler (1977) [15] defined the criteria of local and global structural damages. Banon et al. (1981) proposed the damage index based on the initial stiffness ratio at the maximum displacement of the pushover curve, and formability factors were used to specify the damage model in 1982 [16]. Krawinkler et al. (1983) proposed a cumulative damage index proportional to structural performance parameter, plastic deformation, deformation, and total number of cycle motions [17]. Park et al. (1984) postulated a substantial evolution of vulnerability. They applied the ductility and energy absorbed by structural elements to the damaged members while accounting for more detailed models of nonlinear behavior of RC members under oscillatory loads [18]. Park and Ang (1985) proposed a new approach based on the maximum deformation of the member and integration with absorbed energy [19]. Roufaiel and Meyer (1987) evaluated the seismicity of steel and RC structures and created a structural characteristics-based total structure index [20]. Powell and Allah Abadi (1988) provided an estimate of the damage index based on comparing structural capacity during earthquakes [21]. Corteza (1993) articulated a similar relationship, although his was based on the ductility and energy of the absorbed hysteresis [22]. Bracci et al. (1989) [23] created the global damage index for structures. Krawinkler and Nasser (1992) investigated structural element failure using ductility and cumulative damage indices. The corresponding ductility is determined in this approach assuming an acceptable degree of damage, and then the strength required to limit the demand ductility to the current capacity is calculated, providing an overview of the structure's behavior [24]. Kevil Oghlo et al. demonstrated the frequency variation of the first vibrational mode due to stiffness and strength loss (1994). They anticipated the first vibration mode, as well as local and global damage, by studying hysteresis curve behavior [25]. Dali and Korol (1996) presented a damage index based on the Park damage index [26]. Ghobarah and Abu al-Fattah (1997) developed a damage index approach based on structural response and stiffness measurements of different building classes, which is carried out by static load analysis before, during, and after the earthquake [27]. Ghobarah and EI-Attar (1998) provided a novel method for calculating damage concentration in RC frames. This approach obtains an adequate evaluation by requiring the magnitude of the structure reaction, ground acceleration, and the first two frequencies of ground motion, resulting in an appropriate assessment [28], especially when the damage is concentrated at a certain level of the structure. Following the 1999 Taiwan earthquake,

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John Miyakoshi compared the earthquake damage to building collapses in the Chi-Chi and Kobe earthquakes, resulting in a new formula for determining the building failure index. A compilation of empirical data [29] was used to select the schools. Mikami and Imura (2000) devised a novel relationship in which the maximum fluctuation and resistivity of steel were taken into account [30], with the assistance of Park and Ang (1985) in the elastic range and softness. Papadopoulos et al. (2004) established a criterion for deterioration measures based on plastic joints in columns in a simple but accurate manner that, in addition to the preceding approaches, was also convenient [31]. Abbas Nia and Electric (2004) examined and criticized Park and Ang's damage index [32] by analyzing a total of 25 RC columns with a specific loading history. Kianfar, Estekanchi, and Vafaei (2004) evaluated the performance of third and seventh floor frames using various damage indices [33]. In a proposal that incorporated a multidimensional relation for the locomotive damage index, Jeong and Elnashai (2006) advocated the construction of fragility curves for irregular constructions [34]. Using experimental data from 95 columns, Barghi and Rajabi (2010) studied the development of a Park-Ang damage model on concrete columns subjected to flexural and cyclic loads [35]. Sadeghi (2011) proposed a simple and exact damage index for evaluating structural damage in a cyclic loading model [36]. Vui Van Cao et al. (2014) [37] revealed a relationship between seismic characteristics of remote fault ground motions and the damage index of short RC frames. Morik et al. (2014) proposed a combined damage index [38] for quantifying the failure of symmetric structures in the plan. Furthermore, Rajeev et al. (2014) published a damage index for concentric braced frame (CBF) designs based on absorbed energy [39]. Abbasi and Mirzaei examined the seismic sensitivity of 7 and 10 story RC frame structures to the damage indices of the class interfaces and the pulp length of the joints in the fragility curve [40]. (2016). Mirzaaghabeik et al. (2016) quantitatively and qualitatively evaluated and compared lightweight steel frame designs taking soil-structure interaction into account using the Papadopoulos damage index [41]. Zameeruddin et al. (2017) assessed seismic damage indices of RC frame structures using nonlinear static analysis [42]. Suraj et al. (2020) proposed drift limits for RC frame staging in raised water tanks for different seismic damage states. Several damage states of the elevated water tank were determined using the Park-Ang damage index. The Park-Ang damage index integrates the results of both pushover and incremental dynamic analyses. Twelve different types of elevated water tanks were designed with various staging heights and tank capacity in mind. To undertake incremental dynamic analysis, a set of twelve genuine earthquake ground motions was used. Based on the regression analysis between damage indices and drift [43], limiting drift values for each damage stage are provided. Zhang (2021) presented a method for determining structural total damage by combining two damage components originating in two vertically opposed directions. Based on the damage index, a new seismic failure checking approach for steel reinforced concrete (SRC) frame structures is proposed. Damage constraints in this methodology match to three Chinese code design requirements, and this damage-based method tries to check the failure state of SRC frame structures [44]. Sadeghi et al. (2021) assessed the performance of a 10-story frame with three suitable lateral systems of moment frame (MF), concentric brace (CB) and buckling restrained brace (BRB) is investigated from the theoretical point of view of seismic damage index. Damage indices such as Drift, Park-Ang, Energy, Deformation, Roufaiel and Meyer and Banon Failure under near-fault earthquakes are calculated and compared based on nonlinear dynamic time history analysis. The results showed that the values of the damage index BRB frame were in the limited range and its performance is more appropriate compared to the other two systems [45]. When pounding effects were included, Hosseini et al. (2022) explored three separate damage indices for detecting nonlinear damages in two close RC structures. For this aim, 2, 4, and 8-story benchmark RC

Moment Resisting Frames with 60%, 75%, and 100% minimum separation distance and no in-between separation gap were selected [46].

3. Modelling Procedure

To estimate seismic vulnerability and determine damage indices, structures must be modeled and analyzed, and if possible, experimental studies and results must be compared. The results of theoretical modeling are useful, but laboratory studies are expensive, so in order to study and compare the amount of damage to members and stories in steel buildings with a moment-resisting frame system and the number of stories (4, 7, 10, 15, 20, and 25), and regular and simple geometry of plan has been used to accurately evaluate the deformation and energy parameters in the studied damage indices. The plan of the investigated structures, the length of the bays, and the height of each story were chosen based on Kumar et al. [47]'s article, as shown in Fig 2. In this work, axis 2 of the aforesaid frames was chosen from the steel buildings to undertake nonlinear dynamic time history analysis and extract the structural damage index. The position of the steel structure's frame is stated in Fig 3, and the configuration of the frames is shown in Fig 4. In this study, frames 4, 7, 10, 15, 20, and 25 stories, 3 and 5 bays were designed. In those frames, the height of story is 3 meters and the length of bays is 4.5 meters. Type of materials were construction steel ST-37 with yield strength of 240 MPa and module of elasticity of 200 GPa were considered. Based on Tab 1, cross sections used for the beams of frames were HEB and for columns, they are BOX. The dead load of stories for all structures was 300 kg/m2, the load dead of the roof floor was 250 kg/m2. In the following, the live load of stories are 200 kg/m2 and the live load of roof floor was 150 kg/m2. In order to calculate the lateral load, 2800 standard, 4th edition was used [48].

Table 1. Cross sections of studied frames.

No. story	Beam sections	Column sections
4	HE240B & HE220B	BOX200X200X20
7	HE280B & HE220B	BOX200X200X25 & BOX200X200X16
10	HE320B & HE300B & HE280 &HE260B	BOX280X280X35 & BOX240X240X40
15	HE400B & HE360B & HE340 &HE260B	BOX300X300X35 & BOX300X300X20 & BOX250X250X20
20	HE500B & HE450B & HE400B & HE360B & HE340 &HE280B & HE240B	BOX400X400X40 & BOX350X350X35 & BOX320X320X20 & BOX300X300X20 & BOX280X280X20 & BOX260X260X16
25	HE600B & HE550B & HE5000B & HE400B & HE360 & HE320B & HE300B & HE260B	BOX500X500X40 & BOX450X450X35 & BOX420X420X20 & BOX400X400X20 & BOX350X350X20 & BOX300X300X16 & BOX280X280X16

Fiber Element (wide distribution of plasticity throughout the member) was utilized to model the frame members (beam-column) to describe the nonlinear behavior, and the nonlinear behavior of steel frame members based on Steel01 is illustrated in Fig 5. Is. It should be mentioned that fiber elements are a model that examines nonlinear behavior in a broad sense and has been able to convincingly demonstrate nonlinear features in steel elements. There are 200 fiber sections, and there are 5 Gaussian integrations along the beam-column elements. Materials are allowed to enter the world of nonlinear behavior in nonlinear dynamic analysis, resulting in massive deformations and energy dissipation due to material, cracking, and failure. The dampening during the analysis can vary from step to step. However, these matrices remain fixed throughout each time step, and

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the model's response to seismic acceleration is determined numerically at each time step. To perform nonlinear dynamic analysis in OpenSees software, each element is divided into ten pieces, and the related stresses and strains are measured at three positions in the upper, lower, and middle corners of each section. It is extracted and the lost cycle energy of each member is estimated from it.

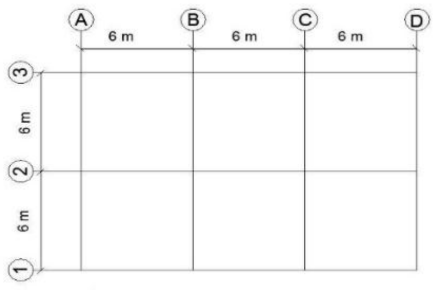


Figure 2. The studied plan of mentioned buildings [46].

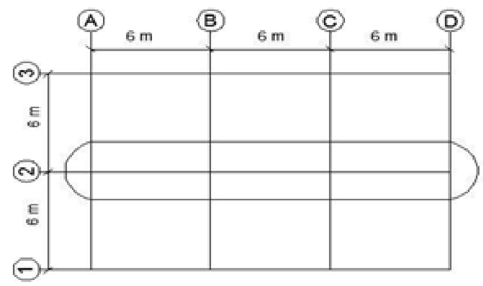
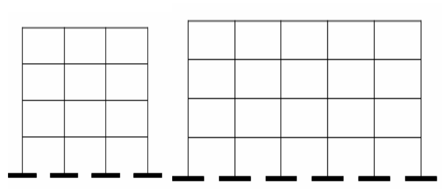
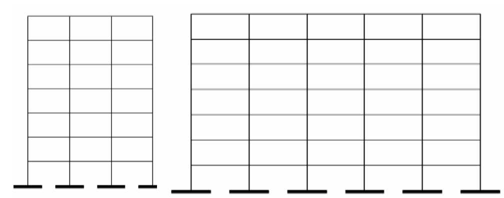


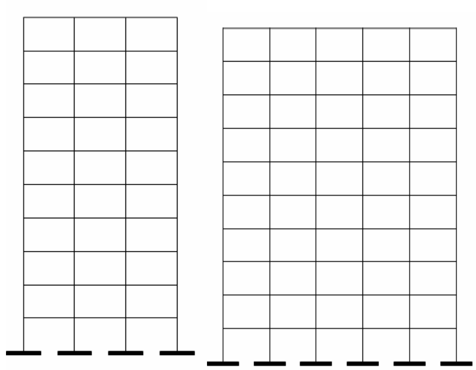
Figure 3. The studied 2D frame in plan [46].



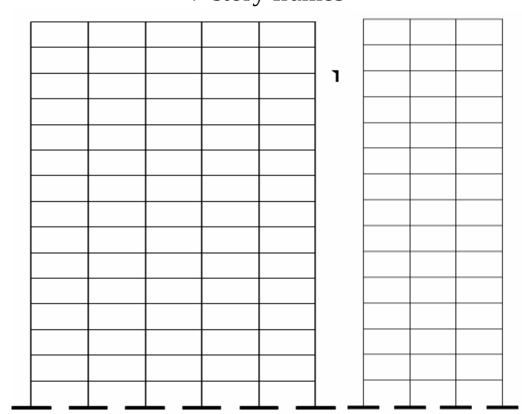
4-story frames



7-story frames



10-story frames



15-story frames

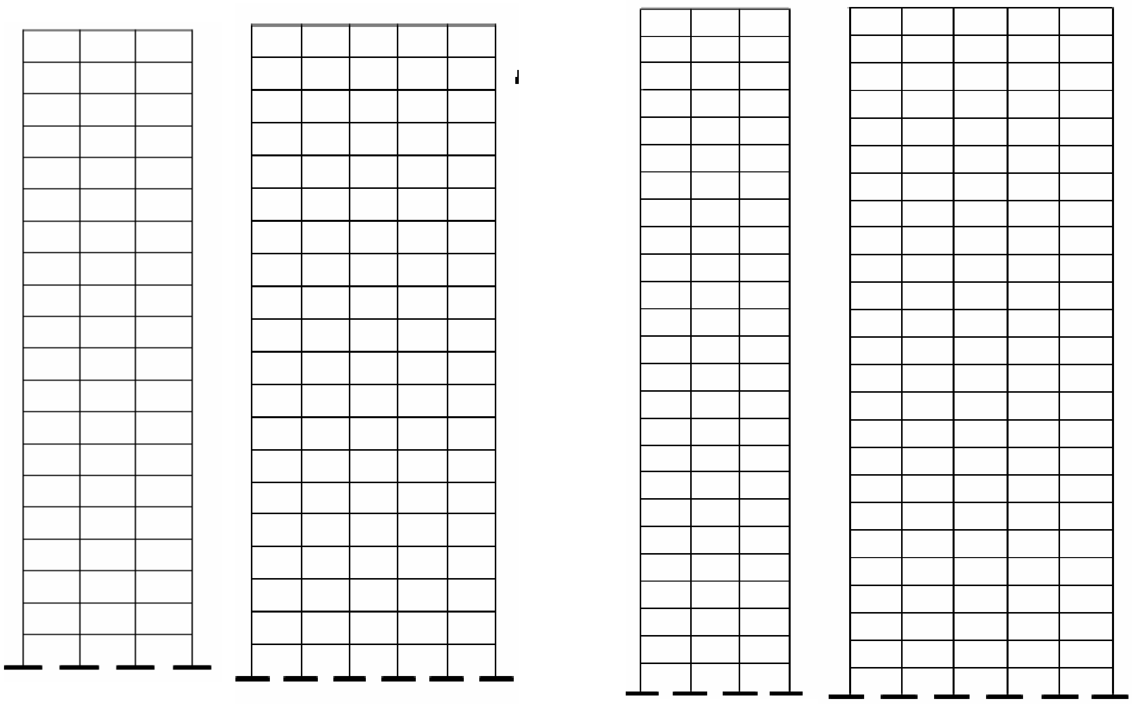


Figure 4. The configuration of the studied frames.

The frames created with this code's spectrum were subjected to the Tabas, Manjil, El Centro, and Borrego Mountain earthquakes, and the values of damage indices for each frame were acquired. According to Fig. 6, the greatest horizontal acceleration values of the Tabas and Manjil earthquakes were 0.82 g and 0.56 g, respectively, whereas the values of the El Centro and Borrego Mountain earthquakes were 0.31 g and 0.06 g. The earthquakes were taken into account in such a way that the differences in damages and functions of various damage indices in frame tales could be evaluated and compared. The OpenSees software was utilized to do nonlinear dynamic analysis. The strain hardening was calculated to be 3% [49-53].

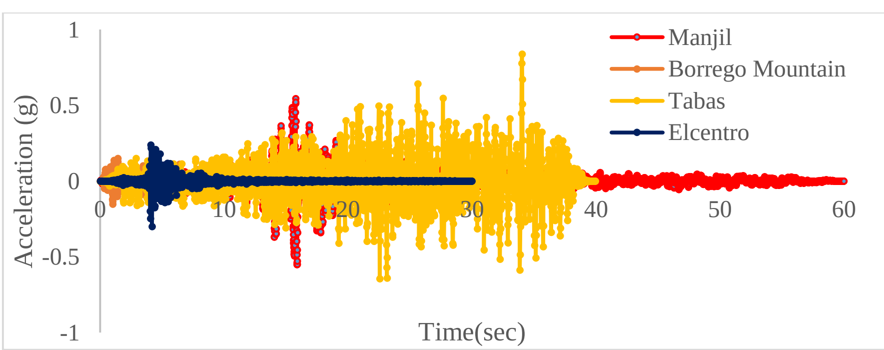


Figure 5. The acceleration-time curve of the studied earthquakes.

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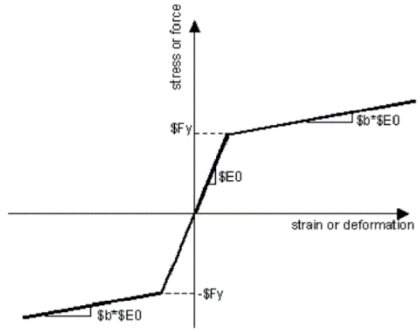

Figure 6. The behavior model of used steel [48-52].

4. The Studied Damage Index

The indicators that show local damage to a member or the entire building when subjected to seismic loading are outlined. In most cases, these indices are dimensionless parameters that take the value zero for the state of no damage and one for the collapse of the structure, with values ranging between zero to one indicating varied degrees of failure. The majority of local damage indices are inherently cumulative, demonstrating damage's dependency on the amplitude and number of load variations.

4.1. Deformation Index Dependent on Deformation

According to Equation (1), the ductility damage index [5] is the most basic definition of a failure function. The ductility damage index does not take into account the amount of energy dissipation by the elements and instead expresses the failure rate using the maximum deformation. DI is the ductility damage index in this equation, θm is the maximum rotation of the end of the member after an earthquake, and θu is the final rotation of the element section. This index's values greater than one indicate element failure.

$$DI_{Ductility} = \frac{\theta_m}{\theta_u} \tag{1}$$

4.2. Energy Damage Index

Unlike the ductility damage index, the energy damage index solely considers energy dissipation by the elements and does not consider their deformation. The influence of earthquake duration on the behavior of the structure and the amount of damage is calculated cumulatively, which is one of the advantages of indices. Equation (2) [54] is used to calculate the energy damage index. The energy dissipated by the elements and My is the yield point of the member in EH equations.

$$DI_{Energy} = \frac{\mathrm{EH}/M_y\theta_y}{(\theta_u/\theta_y \ - 1)} \tag{2}$$

4.3. Combined Damage Index

Indices that account for the effects of deformation as well as the dissipated energy of the elements as a whole may be more reliable. Equation (3) is used to define the Park-Ang damage index for this purpose. This indicator has been routinely utilized in studies to assess the failure rate of concrete beam elements and has also been employed in the case of steel elements [18]. The numerical value of β is experimentally defined as 0.15. Values greater than one indicate the heavy failure and collapse of an element or a structure [19].

$$DI_{Park-Ang} = \frac{\theta_m}{\theta_u} + \beta \frac{\mathrm{EH}}{M_y\,\theta_u} \tag{3}$$

5. Results and Discussions

To study and analyze the total damage of structures, the frames subject of study have been divided into three groups:

Group I: Low-rise frames including 4 and 7-story frames.

Group II: Mid-rise frames including 5 and 10-story frames.

Group III: High-rise frames including 20 and 25-story frames.

Based on Fig 7, rotation time history of the left end of the beam in the left bay of first story of 4-story frame with 3-bay is presented. Also, Fig 8 shows the amount of energy parameter under Tabas earthquake for the ends of beam elements. In the following, Fig 9 indicates moment-rotation hysteresis curve of the left end of beam in left bay of the first story of 4- story 3 bay frame under the studied earthquakes. Figs 10 to 15 show the values of deformation and energy damage indices and also the combined index of Park-Ang. The horizontal axis of these diagrams expresses the values of damage indices and the vertical axis expresses the relative height of the frames. According to the diagrams related to the indices of deformation of concerned frames, it could be observed that deformation of story elements under Tabas earthquake was higher than other earthquakes. It is evident that the deformation damage index leads to collapse of elements for the values larger than one at these indices. As it could be seen, under Tabas earthquake, deformations of elements of 15-story with 3 and 5 bays in the 2nd to 5th stories and in 13th story caused collapse without calculating energy factor. In these stories the deformations needed were larger than the permitted deformations as obtained. In 10 to 25-story frames, deformation of frame elements under Manjil and El Centro earthquakes did not show significant differences. This could be more tangible in the 10 and 15-story frames. Under Tabas earthquake, the deformation of elements of story was higher in the first 50% of frames heights. Under other earthquakes, the changes in the damage index of deformation in the height of frames, particularly 10 and 15-story are not tangible. The highest amount of damage index of deformation under Tabas earthquake is for 15-story frame, the relevant amount was 1.6 and related to the third story. The values higher than 1 show that the elements fracture due to the effects of rotations that exceed the performance limits. In this condition, the maximum demand of rotation is more than the final capacity of elements rotation. The least amount of the deformation damage index under Tabas earthquake was for 4-story frames. Under Manjil earthquake, the highest value of deformation damage index was 0.4 for 20 and 25-story frames. Amount of deformation damage index of the 13th story in the 15-story frame with 3 bays is 0.42. The least amount of this index under this earthquake is 0.11 and is for 4-story frame. The values of this index increases as the height of frames increases. In El Centro earthquake the highest amount of the index is 0.4 for 20-story frame in the third story. The highest amount of this index under Borrego mountain earthquake is 0.17 as related to the 25-story frames.

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By studying the results of energy damage index show that energy absorption by frame elements under Tabas earthquake was higher than other earthquakes. Regarding the energy damage indices, the energy dissipation of elements under Tabas earthquake is tangible. In Manjil earthquake, frames 4 and the 20-story absorbed energy. Under El Centro earthquake; too, only the 20-story frame shows energy absorption and amount of energy dissipation of other stories is not tangible compared to Tabas earthquake. Amount of energy dissipation of frames stories under Borrego Mountain earthquake is ignorable.

With respect to the associated effects of deformation and energy absorbed in Park-Ang damage index, a more suitable and assured values could be found to compare amount of damages of frames and stories. According to the relevant results, under Tabas earthquake, the highest value of this index was 1.6, related to the 15-story frames. The highest amount of this index was 1.2 for 7-story frames and 1 for the 10-story frames. The highest amount of Park-Ang damage index is 0.9 and 0.85 for 20 and 25-story frames were; respectively. With regard to the cross section of beams and columns, the damage indices changes in stories with cross section variations was observed. Changes in the cross section of beams and columns in the frames height some when has caused tangible changes in their indices of deformation, energy and Park-Ang damage indices, compared to their adjacent story.

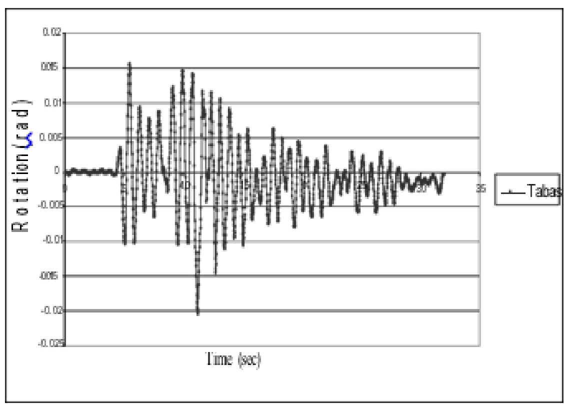


Figure 7. Rotation time history of the left end of the beam in the left bay of first story of 4-story frame with 3-bay.

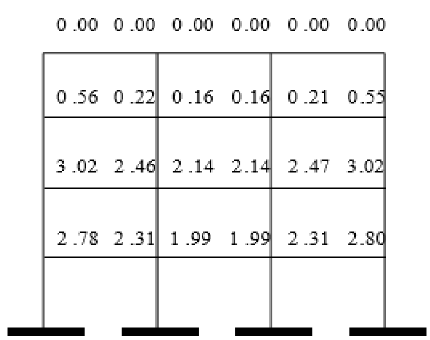


Figure 8. Amount of energy parameter under Tabas earthquake for the ends of beam elements in 4-story with 3 bay (ton. met).

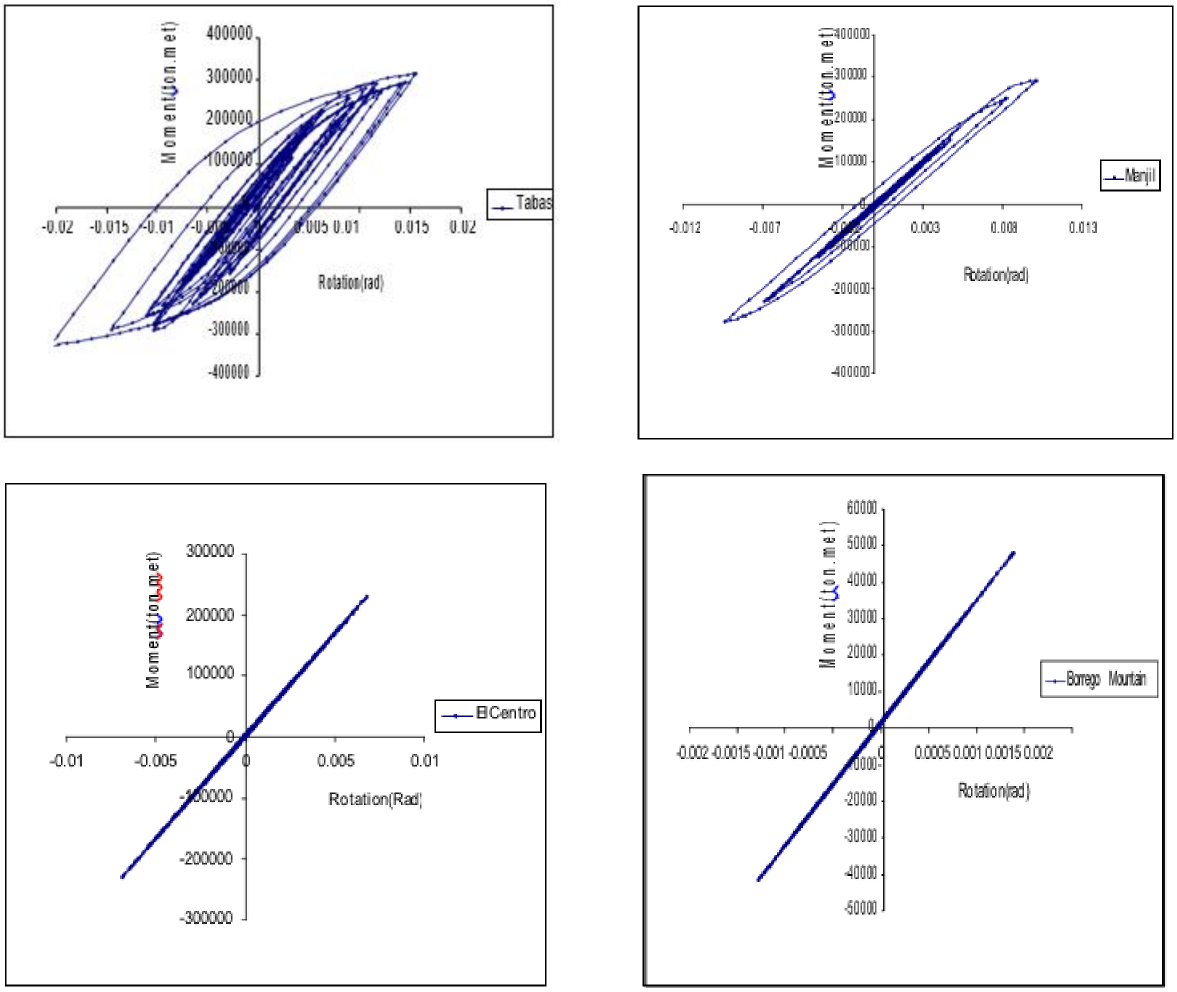
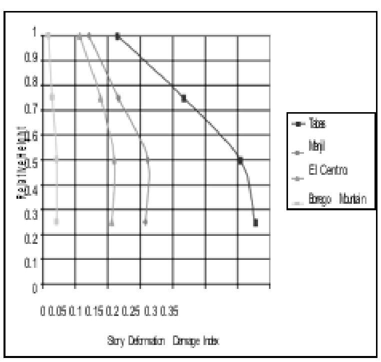
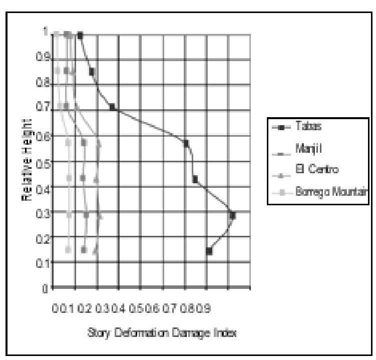


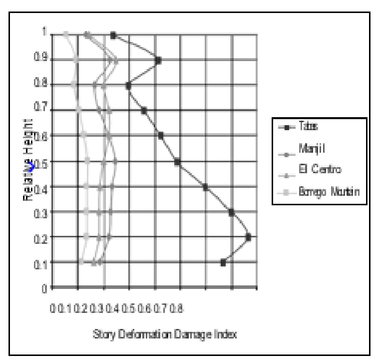
Figure 9. Moment-Rotation hysteresis curve of the left end of beam in left bay of the first story of 4 story with 3 bay frame under the studied earthquakes.



4-story frame



7-story frame



10-story frame

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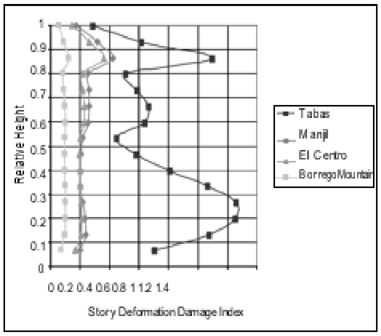
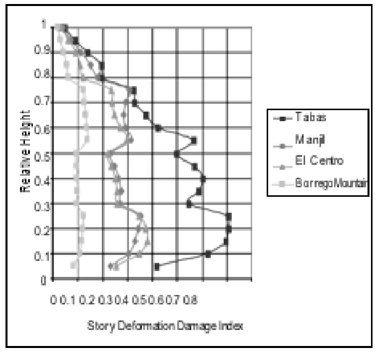
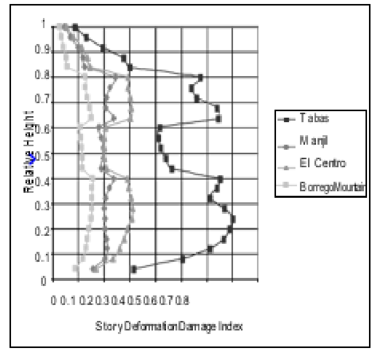
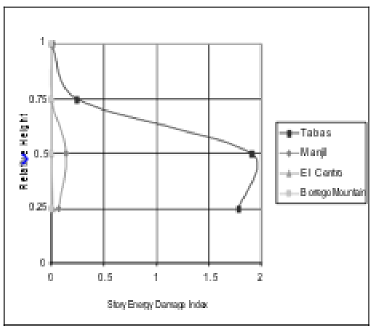


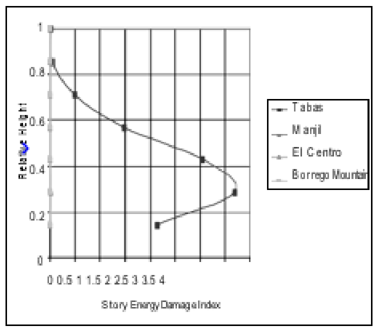


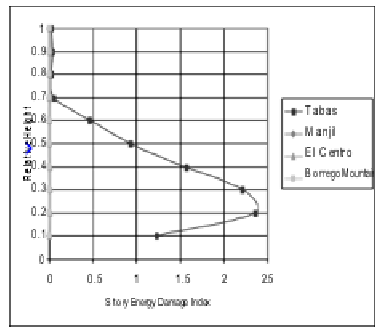


15-story frame **20-story frame** **25-story frame**

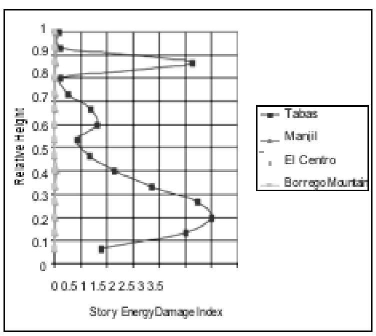
Figure 10. Story deformation damage index under the studied earthquakes for mentioned frames with 3-bay.

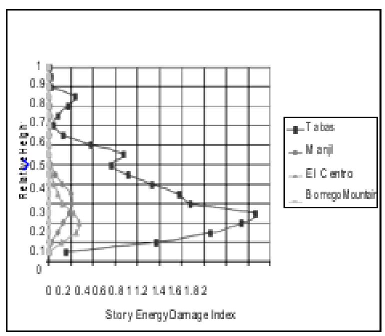


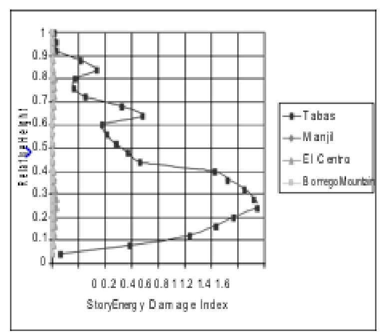




4-story frame **7-story frame** **10-story frame**

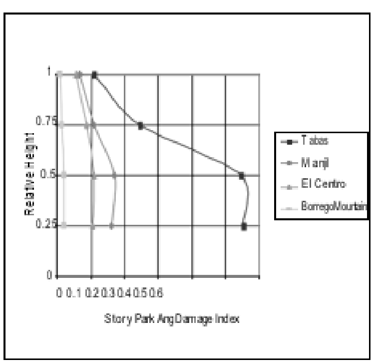


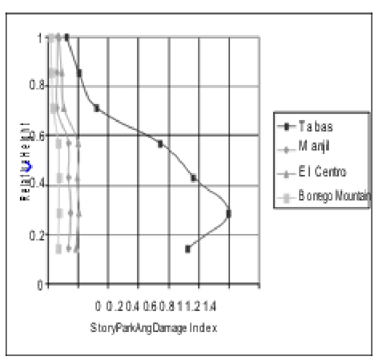


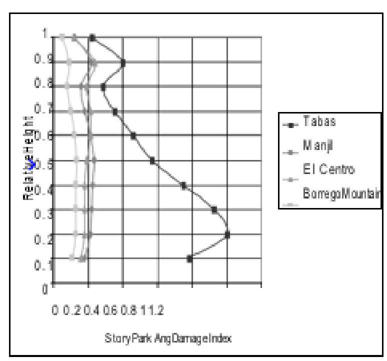


15-story frame **20-story frame** **25-story frame**

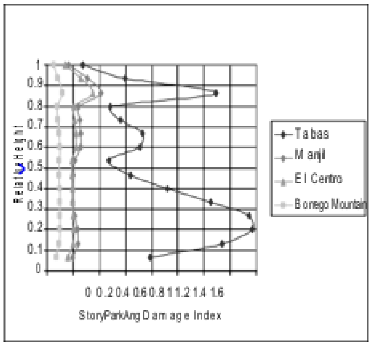
Figure 11. Story energy damage index under the studied earthquakes for mentioned frames with 3-bay.



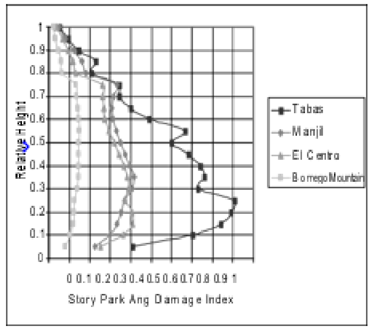




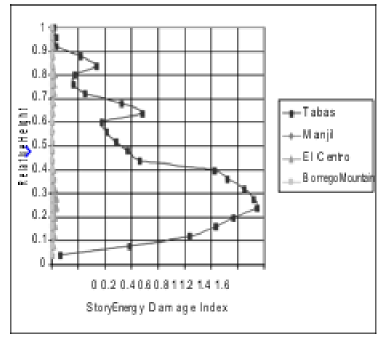
4-story frame **7-story frame** **10-story frame**



15-story frame

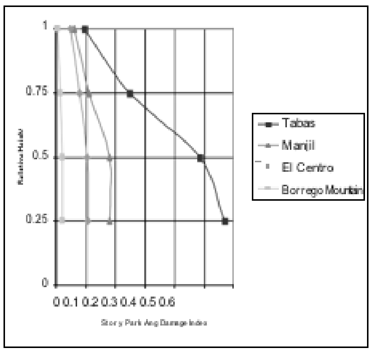


20-story frame

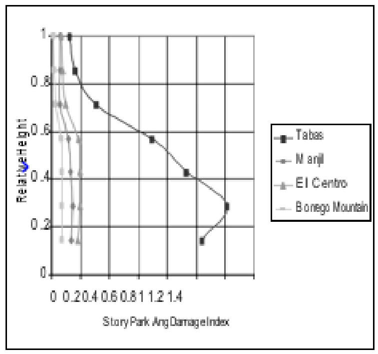


25-story frame

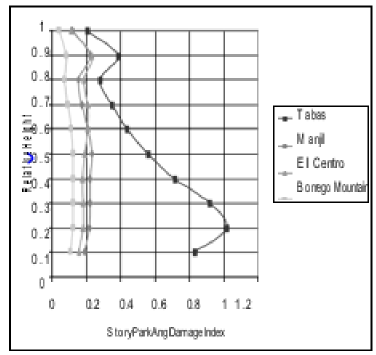
Figure 12. Story Park-Ang damage index under the studied earthquakes for mentioned frames with 3-bay.



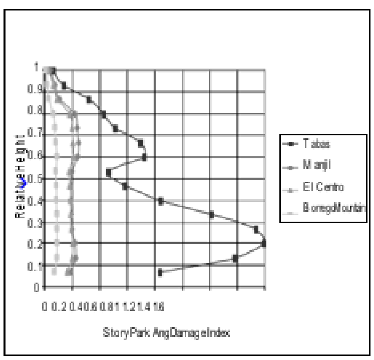
4-story frame



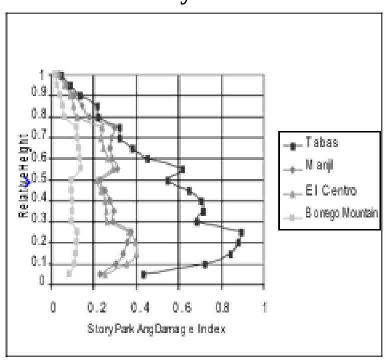
7-story frame



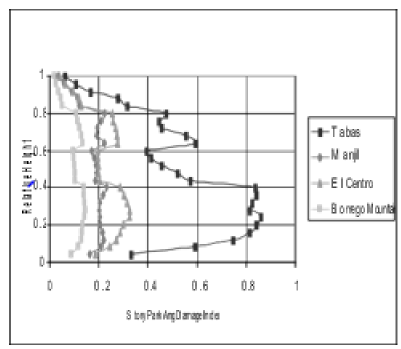
10-story frame



15-story frame

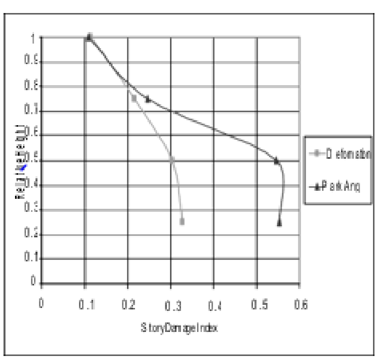


20-story frame

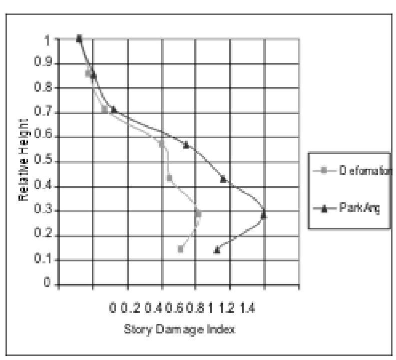


25-story frame

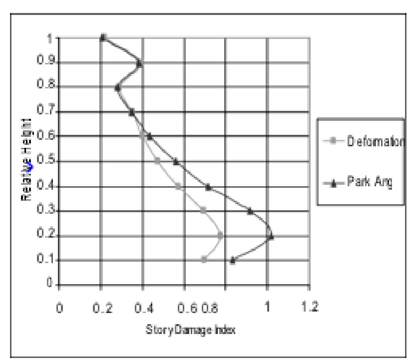
Figure 13. Story Park-Ang damage index under the studied earthquakes for mentioned frames with 5-bay.



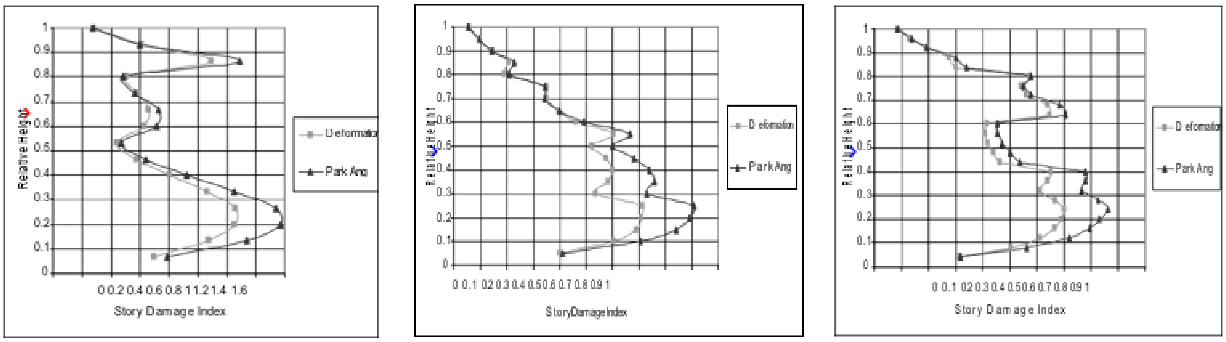
4-story frame



7-story frame

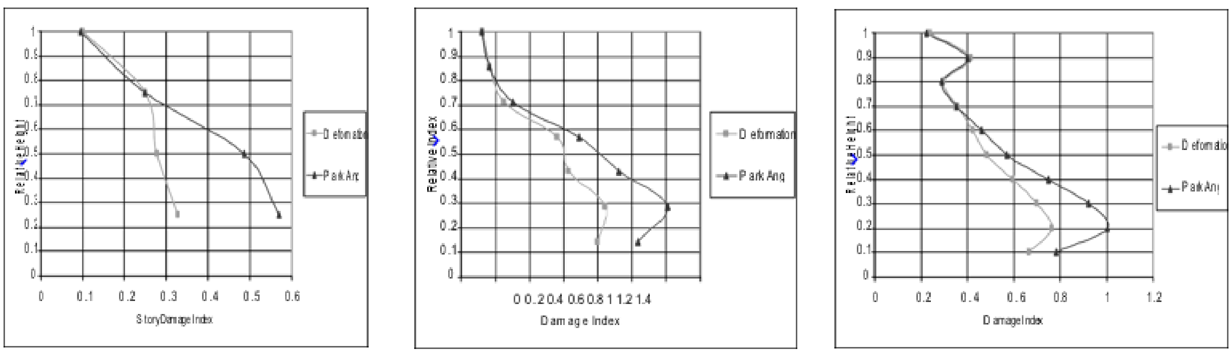


10-story frame

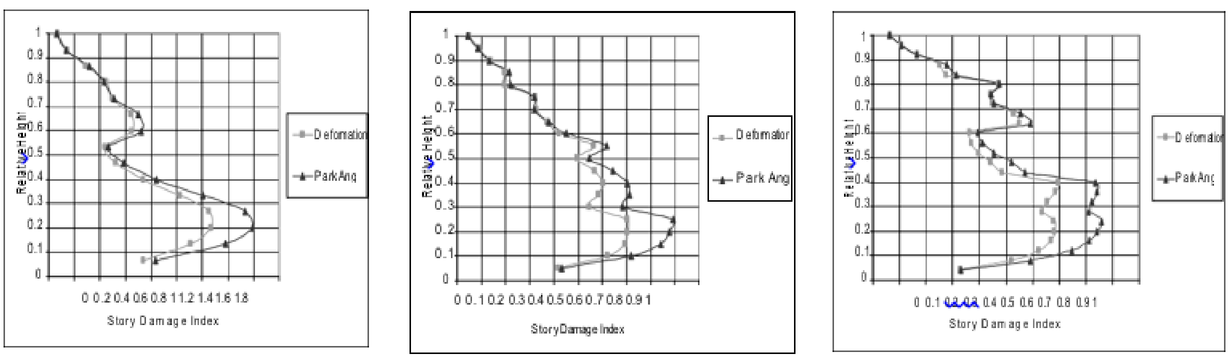


15-story frame **20-story frame** **25-story frame**

Figure 14. Comparison of story Park-Ang and deformation damage indices under the studied earthquakes for mentioned frames with 3-bay.



4-story frame **7-story frame** **10-story frame**



15-story frame **20-story frame** **25-story frame**

Figure 15. Comparison of story Park-Ang and deformation damage indices under the studied earthquakes for mentioned frames with 5-bay.

6. Conclusions

It was attempted to model, construct, and perform nonlinear dynamic time history analysis for multi-story steel moment-resisting frame structures using OpenSees software in order to explore seismic vulnerability and calculate seismic damage indices such as (local and global). Deformation, energy, and Park-Ang damage indices are used in this research. Meanwhile, Park-Ang damage index can be utilized as a guideline for assessing damaged structures. As a result, structural responses were found for each state. The following are the most notable conclusions based on the investigations and analysis conducted:

-The damage patterns were found to vary from one earthquake to another. Under Tabas earthquake, damage is more significant in the first 50% of frame height. The story damage in the first 25% of frames is higher.

-The most frames that have been analyzed subjected to the El Centro earthquake ground motion have a damage index in the range of 0.0 to 0.4. This low index shows that frames have only light or moderate damage level. This situation exists for Manjil and Borrego Mountain Earthquakes. It can be concluded that high-rise frames in this study are affected by these earthquakes more than the low-rise frames.

-Energy dissipation of story of frames under Tabas earthquake was more significant. Energy dissipation in story of frames under other earthquakes was lower rate.

-The values of damage indices that consider both the effects of deformation and energy dissipation could indicate reality in a higher degree. As an example, as it was observed, the damage index based on deformation on the 10-story frame does not show the story collapse and value of deformation damage index in this story was 0.77. The mixed effect of energy and deformation has placed this story in the threshold of collapse. The value of combined damage index of Park-Ang in this storey is 1.

-Amount of damage in 15-story frame was higher than other frames. 7 and 10-story frames faced elements collapse. The least damages in terms of Park-Ang criteria was for 4-story frame.

-The values of Park-Ang damage index in stories with larger energy dissipation was more than values of deformation damage index. For 3-bay frames, under Tabas earthquake, in 4-story frames, highest value of deformation index was 0.3 and highest value of Park-Ang damage index was 0.54. The share of deformation in Park Ang criteria was 56% and the energy share was 46%. For 7-story frame, the highest amount of deformation damage index was 0.82 and Park-Ang damage index was 1.18. Share of deformation in Park-Ang damage index was 73% and share of energy was 27%. For 10-¬story frame, highest amount of Park-Ang damage index was 1 and highest value of deformation damage index was 0.77. Share of deformation was 77% and share of energy was 23%. The highest value of index in Park-Ang damage index in 15-story frame was 1.6 and highest value of deformation damage index was 1.3. The share of deformation was 82% and share of energy was 18%. Regarding 20-story frame, the highest value of Park-Ang damage index was 0.91 and the similar value of deformation damage index was 0.71. The share of deformation in Park-Ang criteria was 78% and share of energy was 22%. This share is 82% for deformation and 18% for energy in the 25-story frame. The same results can be observed for 5-bay frames.

-The studied frames have shown acceptable performances under Manjil, El Centro and Borrego mountain earthquakes; however, 7, 10, and 15-story frames faced collapse of stories under Tabas earthquake.

-Effect of amount of energy dissipation in the values of Park-Ang damage index for low-rise frames especially 4-story frame is clearer.

-With respect to the results obtained in the studies, largest damages were observed under Tabas earthquake and the least damages were noticed under Borrego Mountain earthquake.

-Due to consider the both factors of deformation and energy in estimating amount of damage and due to the significance of specific ranges in quantitative interpretation of amount of damage, Park-Ang damage index is more likely to express the realities.

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