Probabilistic Evaluation of Damage Index of Steel Moment Frames at Different Performance Levels

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Abstract: According to the performance-based design method, damage levels of the structure and their corresponding displacements are presented both qualitatively and quantitatively. For quantitative evaluation of seismic damage level in structures, damage index is used. Researchers have been proposed several functions based on the nonlinear dynamic and cyclic behavior of the structural members for quantitative evaluation of damage. On the other hand, for evaluation of damage index, various uncertain parameters such as load and resistance exist. In this paper, a modified damage index based on the reduced stiffness of the structure is introduced. Results from the modified damage index are compared with those indices which are based on energy and the period of the structures. Results show that the proposed damage index is an appropriate factor for damage evaluation of steel structures specially. Three groups of structures including 3, 6 and 12 stories structures and also their uncertainties and probabilistic sources were considered. The damage index and the drift of the structure for each performance level were determined. Sensitivity of the damage index with respect to the uncertainties parameters in performance level is indicated. Furthermore, the quantitative damage of the structures with their corresponding drifts is obtained.

Key words: performance levels, damage index, uncertainty, probabilistic analysis, pushover analysis.

INTRODUCTION

Although the designed structures based on seismic criteria have exhibited acceptable performance in preserving life safety in recent earthquakes, the extent of damages to structures and recompenses have been extensive and unpredictable. However, it is clear that the designed structures based on these seismic criteria undergo extensive damages against high magnitude earthquake. Therefore, performance based design is considered as a methodology whereby expected displacements and deformability can be limited to the accepted level, corresponding to the specified performance levels. Predicting a clear picture of the amount of damages to the structure at different hazard levels is one of the most important issues in performance based design. There are different levels of damages to structures specified in some codes such as FEMA-273 (1997) and ATC 40 (1997). The determinative criteria of the structural status in these codes are based on lateral deformations. In general, damages to a structure could be defined as decrease in the structural capacity under different loading levels compared to the intact structure before the earthquake or any other loading that may happen. Researchers have introduced various methods which help to estimate the amount of damages in order to determine the damage index (Stephens and Yao, 1987). The study of the history of these methods shows that although some of the indexes have adequate consistency with the observed damages to the structure, their calculation process requires nonlinear dynamic analysis, which is sometimes complicated and time consuming. Furthermore, intrinsic uncertainties incorporated in the loads and strengths, also in earthquake characteristics, show further investigation is required to examine these indexes in much more complicate state. Several researches carried out in this field can be related to the works of Stephan and Yao (1987), Usami and Kumar (1998) and Kolombo and Negro (2005). Usami and Kumar (1998) developed a model for estimation of damage index capable of assigning large deformation for steel bridges. Colombo and Negro (2005) proposed an index based on strength loss. The index presented by Stephan and Yao (1987) is also established on dynamic response of the structure and the hysteretic energy loss. It is possible to estimate the structural capacity using pushover analysis without including complicated nonlinear dynamic analysis. If an index is introduced based on the pushover analysis to suit a single structural performance point, namely consistent with the specific structural state, it will be possible to specify structural damage index in terms of performance point.

In performance based design, a specific target level is defined for structural performance and the structure is designed for that level. There are four different levels defined in the FEMA-273 (1997): operation prevention (OP) in which the structure does not undergo any damages, immediate occupancy (IO) where the structural elements are partially damaged, life safety (LS) when structural and non-structural elements are remarkably damaged and finally collapse prevention (CP) in which the structure is about to collapse. According to this classification, the defined levels are of qualitative manner and there is no quantitative criterion to specify a
specific limit for performance levels. On the other hand, the existence of uncertainties in the process of determining performance point sophisticates the quantitative definitions of the code. The aim of this paper is to quantify the above qualitative limits at performance levels and to investigate the sensitivity of damage index considering uncertainties at different performance levels. As a result, it could be obtained that to which uncertain parameter the sensitivity is higher at each performance level, so as to concentrate on those specific parameters in the designing process.

2. Methods to Determine Damage Index:

Quantifying damages in structures after earthquake is one of the most important and interesting issues that have been investigated by several researchers. Defining the degree of damage as the function to dynamic response of the structure is one of the methods of quantifying damage index in structures, presented in the researches carried out by Park and Ang (1985) and Cosenza et al. (1993). Rodriguez (1994) developed a method based on plastic energy absorption in cyclic loading. Another technique is the “damage index” of lateral displacement cited in FEMA-273 (1997). This index is one the most important indexes in the category of general index of the structure (FEMA-273, 1997) offered as follows:

$$DI = \frac{\Delta m}{H}$$

(1)

where $\Delta m$ is the maximum roof displacement corresponding to a single performance point, and $H$ is the height of the structure. The results of researchers Cosenza, E., Manfredi, G. and Ramasco, R (1993), indicate that the displacement index obtained based on Eq.(1) could not suitably present the damage, which can be related to the absence of the ultimate capacity of the structure in this equation.

In recent years, another interesting damage index has been introduced by some researchers which takes the stiffness before and after earthquake into account in order to determine damage index. Otani and Sozen (1972) monitored that based on the experimental observation from multistory frames, if a building structure at a large earthquake enters the yielding phase and then attacked by the second similar earthquake, the maximum lateral displacement associated with the first and the second earthquake are the same, but the stiffness of the structure at the beginning of the second earthquake is lower than the stiffness of the first earthquake. They concluded that the maximum drift depends on the primary characteristics of the structure and independent of the stiffness of the structure at the beginning of the second earthquake experiment. Therefore, drifts cannot be merely considered for the assessment of damages index. The idea of damage index introduced by Ghobarah et al. (1999) was based on structural stiffness formulated with the following expression:

$$DI = 1 - \frac{K_{\text{final}}}{K_{\text{initial}}}$$

(2)

where $DI$ is damage index, $K_{\text{initial}}$ is initial stiffness or the initial tangent of the base shear-roof displacement curve before the earthquake impact and $K_{\text{final}}$ is the tangent of the curve after the earthquake impact. The amount of $DI$ ranges from zero to one; zero represents no damages and one represent incipient collapse of the structure.

Another technique for determining damage index is the energy based method. The dissipated energy by the structure has been utilized by several researches to determine damages to the structure, most of which are based on dynamic analyses. Kato and Akiyama (1975) considered the accumulated energy by hysteresis damping as a factor for estimating structural damages. Zhang et al. (2007) employed the applied energy on the structure and plastic energy of the structure in order to determine the extent of damages to the structure. Therefore, this index can be estimated by the following expression:

$$DI = \frac{E_p - E_i}{E_f - E_i}$$

(3)

where $E_p$ is the area under structural capacity curve at an arbitrary point, $E_i$ is the area under the curve at the corresponding point to the entrance of the structure to nonlinear phase, and $E_f$ is the area at the corresponding point to the collapse of the structure. The limit for $E_p$ is considered as the point right after the first yielding point of the structure, therefore as the structure enters the nonlinear zone, $E_p$ equals $E_i$ and the damage index equals zero. The more the structure enters the nonlinear phase, the more structural elements undergo damages, and the index amount increases. At the corresponding point to the collapse of the structure, $E_p$ equals $E_f$ and the index amount equals 1. Specifying the collapse point of the structure ($E_c$) can affect on the damage index. Researchers have introduced different definitions for the collapse point of the structure (Powell H.Graham, Allahabadi R,
Most of them consider the ultimate collapse point of the structure a point on the capacity curve at which the structure undergoes huge sudden deformations compared to the previous step as the lateral force gradually increases. This is a jump in the capacity curve of the structure, which is considered in this research as ultimate collapse point.

The methods of considering damage index deal with the vibration period of the structure. In fact, the vibration period of the structure is one of the most important characteristics of the structure that can be used for indicating the structural stiffness and vibrating movement. In an intact structure without damages, the structure exhibits linear behavior and its period corresponds to its stiffness. As the structure enters the nonlinear phase, the structural period increases due to the reduction in the lateral stiffness and yielding of some elements. Theoretically, by the reduction of structural stiffness, the period of the structure increases, up to the ultimate period, where the structure collapses and the stiffness equals zero. Therefore, this index is defined as

\[ DI = 1 - \frac{T_e}{T_i} \]  

where \( T_e \) is the structural period in the plastic zone and \( T_i \) is the structural period at each step of the nonlinear analysis. \( T_e \) equals \( T_i \) at the first step of nonlinear analysis; therefore damage index will be zero at this point. The stiffness of the structure reduces as it enters the nonlinear phase leading to an increase in the period of the structure, with the consequence that the stiffness equals zero at the point corresponding to the collapse of the structure.

3. Damage Index Based On the Stiffness at Different Performance Levels:

In this section, the stiffness based damage index presented by Ghobarah et al. (1999) will be modified in order to apply for evaluating structural performance at different performance levels. In general, a structure with usable performance level, having an elastic behavior is called an intact structure. On this basis and considering the fact that the calculated stiffness in pushover analysis is not an acceptable criterion of structural stiffness at the beginning of loading process and due to non-structural elements in the building, it is better to determine damages of other performance levels to the usable level. Therefore, the extent of damages index for other performance levels can be introduced with the following equation:

\[ DI_j = 1 - \left( \frac{K_j}{K_{OP}} \right) \]

where \( (DI)_j \) is damage index at the specific performance point, \( K_j \) is the tangent of base shear-roof displacement curve associated with the specific performance level \( j \), and \( K_{OP} \) is the tangent of base shear-roof displacement curve associated with the performance level OP. Damage extent at different performance levels ranges from zero for applicable levels to one for collapse levels. Energy based damage index and structural period based damage index for different performance points can be estimated by equation 5. In order to consider and compare methods of determining damage index, structural damage extent are evaluated using equations 3, 4 and 5 at four performance levels conforming to FEMA-273 (1997).

4. Uncertainty:

Structural designing process in civil engineering comprises different uncertainties, some of them are known and clear, the others are unknown due to being covered. Damage index is related to different performance levels. Therefore, sources of uncertainty are the same in both estimating damage index and performance point. The most important sources of uncertainty in the process of determining performance point are uncertainty in structural loads, uncertainty in strengths, uncertainty in the modeling, and uncertainty in the methods of determining performance point.

In the previous researches (Azhdary, F. and Shabakhty, N. (2011)), uncertainty resources and probability functions corresponding to each variable are investigated. In this study, based on the previous results, sources are generally classified into the following two groups; uncertainty in loads; uncertainty in the strength of structural elements. Uncertainty in loads is also divided into three major groups of uncertainty in dead load, live load and lateral load. In Table 1, the type of the selected probability distribution function as well as corresponding coefficient of variation of dead and live loads are presented.
Table 1: Characteristics of Random Variables Selected in this Research.

<table>
<thead>
<tr>
<th>Sources of uncertainty</th>
<th>Variable</th>
<th>Probability distribution</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in loads</td>
<td>Dead load</td>
<td>Normal</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Live load</td>
<td>Log-Normal</td>
<td>0.35</td>
</tr>
<tr>
<td>Uncertainty in the strength of structural</td>
<td>Modulus of elasticity</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>elements</td>
<td>Yield and ultimate stress</td>
<td>Log-Normal</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Geometrical properties</td>
<td>Normal</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Uncertainty in the strength of structural elements is also added by introducing three major parameters, namely; modulus of elasticity; yield and ultimate tensile stresses of elements; and geometrical properties of sections in the analysis. To chose uncertainty function characteristics are selected from (Bilal M. Ayyub (1998), Huh, J. and Haldar, A. (2002), Ranganathan.R.(2000), William M. Bulleit , M.ASDE.(2008)).

5. Numerical Study:

In order to investigate behavior of different types of buildings, we consider three types of buildings in this research; namely, 3, 6 and 12-story buildings, as shown in Fig. 1.

These buildings generally represent the low, middle height and high-rise buildings, respectively. According to the studies of Stafford and Coull (1991), buildings in which the height is less than three times the span length, are low height and buildings in which the height is more than three times the span length are considered as high-rise buildings and those buildings which stand between these two ranges are middle height buildings. The height of each story in the model is presumed 3.2 meters and the beam span is 4 meters. The distance between frames is assumed to be 4 meters. Since it is generally allowed to study a 2-dimensional (2D) model and then generalizing the results to a 3-dimensional (3D) model on condition that no remarkable torsion happens in the 3D model (Iranian Loading Code, 2006), 2D frames have been used in this research. Section properties of selected members of frames are presented in Table 2.
Table 2: Section Properties of Columns (C) and Beams (B).

<table>
<thead>
<tr>
<th>Mean values</th>
<th>BOX 18×18×0.8</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Es = 21000000 kg/cm²</td>
<td>BOX 20×20×1.0</td>
<td>C2</td>
</tr>
<tr>
<td>Fy = 2400 kg/cm²</td>
<td>BOX 26×26×1.0</td>
<td>C3</td>
</tr>
<tr>
<td>Fu = 3700 kg/cm²</td>
<td>BOX 30×30×1.2</td>
<td>C4</td>
</tr>
<tr>
<td></td>
<td>BOX 34×34×1.2</td>
<td>C5</td>
</tr>
<tr>
<td></td>
<td>BOX 38×38×1.5</td>
<td>C6</td>
</tr>
<tr>
<td></td>
<td>IPE27</td>
<td>B1</td>
</tr>
<tr>
<td></td>
<td>IPE30</td>
<td>B2</td>
</tr>
<tr>
<td></td>
<td>IPE33</td>
<td>B3</td>
</tr>
<tr>
<td></td>
<td>IPE36</td>
<td>B4</td>
</tr>
<tr>
<td></td>
<td>IPE40</td>
<td>B5</td>
</tr>
<tr>
<td></td>
<td>IPE45</td>
<td>B6</td>
</tr>
</tbody>
</table>

The chosen sections for columns are box shapes, and wide flange I shaped sections are selected for beams. The cross sections change for each two or three floors in columns, while beams in each floor take one typical section. These frames sustain the mean dead load of 650 kgf/m² in each floor area and 600 kgf/m² for roof area. The mean intensity of live load for typical floors and roof is assumed as 200 kgf/m² and 150 kgf/m², respectively. The difference in loads between typical floors and roof is arises from different construction details for floors and roof. The structure is designed based on the tenth volume of Iranian national building regulations (2006) with the loading values according to the sixth volume of Iranian national building regulations (2006) and the structure is checked in accordance with the Iranian earthquake code, standard 2800 (2006).

Based on the mean values of uncertainty parameters, performance point is calculated according to FEMA273. In this research, the model and its loadings are modified regarding the type of distribution of uncertainty parameters as well as coefficients of variation. Therefore, one parameter is considered variable and the others constant. Other parameters will be assessed after a statistical investigation and integration of statistical population.

Damage index represents the degree of damage may occur at each performance level. Damage extent to the structure also has a direct relationship with the structural stiffness variations. The study of frame stiffness variations will be useful. Therefore, the stiffness variation of the six story frame is estimated and shown in Fig.2.

![Fig. 2: Variations of structural stiffness at different performance levels for six-story frame building.](image)

As it is clear from this figure, structural stiffness has a downward trend at different performance levels, due to entering nonlinear phase as well as successive yielding of load caring structural elements. This figure is extensively used in the structural vulnerability. Another useful application of this diagram is in the classification of code’s performance levels based on the structural power, e.g. a structure with immediate occupancy application has stiffness about 61 percent of the intact structure. This structure exhibits stiffness near 16 percent of the initial stiffness at LS level. Based on the obtained results shown in Fig.2, we suggest for divisions done in the performance levels zoneconsidering effects of reduced stiffness.

In section 2 damage indexes were defined in order to quantify the defined qualitative levels by performance based design codes. This damage index can be calculated using both base shear-structural displacement diagrams with Eq.(2). Variation of damage index with the drift of the structure are estimated and shown in Fig.3 for six-story frame building. As it is clear from this figure, damage index equals zero at operation prevention level (DIO=0), at immediate occupancy level equals 30 percent (DIO=0.3). It is about 83 percent at life story level (DILS=0.83) and 90 percent at collapse prevention level (DICP=0.9). In fact, it is possible to quantify the codes qualitative limits by conducting statistical study into different patterns.
It is not possible to definitely determine collapse zone using base shear-displacement diagram, while the damage index-drift can reveal this zone; a zone in damage index-drift diagram in which damage index variations are low, can be introduce as the structural total collapse zone. It helps the designer to clearly determine structural collapse zone. The important fact is that the zones have a direct relationship with structural displacement; therefore, it is possible to compare the quantitative defined limits in codes in terms of defined area of drift.

In FEMA-273 (1997), linear behavior and drift are introduced lower than 0.7 percent for the OP zone; if a structure exhibits linear behavior with drift lower than 0.7 percent, the level will be OP. Investigations indicate that this part of the code corresponds to the results obtained from damage curve. In this code, drift for IO zone is 1 percent and nonlinear behavior is also defined for this zone. According to Fig. 3, it could be mentioned that this zone does not correspond to the definition by the code. In FEMA-273 (1997), the defined drift for the LS equals 2 percent in which the structure exhibits a nonlinear behavior.

![Fig. 3: Variations of structural damage index at different performance levels for six-story frame building.](Image)

The extracted data from Fig. 3 indicate that the obtained drift in LS zone is 1.3 percent, therefore, it can be concluded that the code related expectations from structural behavior belong to a higher level; not consistent with each other.

The ultimate expectation and definition of the code for CP level is 4 percent, while referring to the diagram, the structure is totally collapsed in 2.5 percent displacement. The reason of inconsistencies between the four defined levels and the structural damage diagram could be attributed to the restrictions of plastic rotation in members. In other words, performance levels are determined based on rotation of plastic hinges. Since, the rotations in the performed design stand in the ranges of the code, it could be concluded that the fulfillment of restrictions of plastic rotations of structural elements has caused inconsistencies between the drifts in the model and permissible limits of the codes, which is also an inconsistency in design permissible limits introduced in codes. Whatever discussed was related to a special structure with certain parameters, therefore, one can reach other useful data by conducting statistical study and working with other parameters with uncertainty. By performing statistical investigations, the sensitivity of uncertain parameters will be determined at collapse levels. It is also possible to quantify the real bounds of each performance level from damage index-drift diagram and clearly realize which uncertain parameter has the most effects on the increase in structural damages. Furthermore the real collapse prevention level of the structure as well as its amount will be calculated without reliability analysis. The study of the sensitivity of parameters on the stiffness variations-displacement curve reveals the effective factors on the increase in structural failure.

**6. Comparison of Damage Indexes for Different Frames:**

In order to study different damage index for a variety of structures, damage indexes are obtained for three structures introduced in section 2 using three methods of stiffness, energy and period. The results are estimated in is shown in Figs. 4, 5, and 6 for three-story, six-story and twelve-story building frames respectively. The letters T, E and K stand for period, energy and stiffness variation methods respectively. The comparison between these different methods can lead to a qualitative assessment of the associated variations.
Fig. 4: Variations of structural damage indexes at different performance levels in the three-story frame.

Fig. 5: Variations of structural damage indexes at different performance levels of the six-story frame.

Fig. 6: Variations of structural damage indexes at different performance levels of the twelve-story frame.

As it can be observed from Figs. 4 to 6, damage index based on dissipated energy method generally gives more value at all levels in comparison with the period variation method. The damage index based on energy method varies between 80 to 85 percent for the CP level, however, the index decreases at CP level as the
number of stories increases. The shortcoming of this index is that its amount depends on determining collapse point of the structure. Firstly the damage limit of the structure is defined, then the limits between an intact structure and damaged structure are divided into different degrees of damages based on the collapse point of the structure. Therefore it is not possible to introduce the collapse point of the structure by this method. The comparison of damage indexes between stiffness based methods and period based methods indicates that stiffness based damage index almost reveals a higher value compared to the period based damage index for all buildings. Variation patterns of stiffness and period based methods are similar in the three-story structure, but they change differently as the height of the structure increases. This characteristic becomes more apparent at the ending part of the diagram in which the structural behavior enters the nonlinear phase. In fact, the rate of damage variations based on structural period has a jump at the end of the diagram, namely, structural collapse point. Damage index based on stiffness based method gives more reasonable results compared to other introduced indexes. The reasons of this advantage could be attributed to two facts; Firstly, damage or ultimate limit of the structure does not need to be defined in introducing stiffness based damage index, and the results could be investigated until the structure exhibits stiffness; Secondly, the obtained results for damage index are statistically more reasonable and no jump could be found in the damage index variations diagram based on stiffness. While, a jump could be observed in damage index variations diagram based on period and this index does not give acceptable results due to local yielding in structural elements.

7. Investigation of the Sensitivity of Variables at Performance Levels According to Damage Index:

Damage index is a measure parameter of the structure that could be expressed at each performance level. This index depends on variables that they are incorporating with uncertainty, namely, dead load, live load, ultimate and yield stress of elements, modulus of elasticity and finally the geometry of element sections. It is of great importance to determine the sensitivity of damage index to random parameters. In this section, damage index will be determined at different levels defined by the code along with the sensitivity to parameters. On the other hand, drift corresponding to the associated collapse is also presented for each frame. The results of this investigation are shown in Table 3 for the three groups of 3, 6 and 12-story frame buildings.

| Table 3: Percentage Coefficient of Variations of Damage Index for Three, Six and Twelve Story Frame Buildings. |
|-----------------------------------|-----------------------------------|-----------------------------------|
| Random Variables                  | Three-Story Frame                 | Six-Story Frame                   | Twelve-Story Frame               |
| Performance Level                 | Performance Level                 | Performance Level                 | Performance Level                 |
|                                  | IO      | LS      | CP      | IO      | LS      | CP      | IO      | LS      | CP      |
| DL                                | 5.75    | 2.64    | 0.38    | 5.21    | 1.97    | 0.24    | 4.47    | 2.04    | 0.24    |
| LL                                | 1.17    | 1.42    | 0.08    | 1.93    | 0.78    | 0.05    | 0.98    | 0.57    | 0.05    |
| FY                                | 3.35    | 4.77    | 0.35    | 2.24    | 3.54    | 0.21    | 1.93    | 2.72    | 0.16    |
| Es                                | 1.32    | 3.65    | 0.18    | 1.93    | 2.92    | 0.16    | 1.73    | 2.04    | 0.11    |

It will be noted that the structural stiffness variations method has been used for calculating damage index. According to Table 3, it could be observed that the highest sensitivity of damage index for all levels is associated with the geometrical properties of sections. At IO level, dead load variations stand in the second place in terms of sensitivity compared to geometrical properties. Live load shows the lowest sensitivity at this level. At LS level, the sensitivity of strength factors such as yield stress and modulus of elasticity is of the second degree of importance because of the initiation of nonlinear behavior in the structure. At CP level, the sensitivity of damage index is lower than other parameters, while the sensitivity of geometrical properties increases. As the number of structural stories increase, the sensitivity of geometrical properties reduces.

8. Suggestion for Quantifying Performance Levels Based On Damage Index:

In this section an investigation is carried out to determine damage index based on the mean values obtained at different performance levels and their corresponding drifts in order to quantify performance levels defined by the code in question. Referring to equation 5, the structure at OP level is called intact structure (DI=0) and the structure at CP level is called collapsed structure (DI=1.0). However, since the structure at CP level is not totally collapsed, the structure can still resist loads, however inconsiderable. Therefore, damage index will not equal 1 at CP level. In fact, collapse prevention will occur at the point at which damage index is lower than 1. As a result, in this paper a drift equal to 97 percent is considered equal to the drift at structural collapse. The reason for selecting this value as damage index refers to two facts. Firstly, in most investigated models damage index corresponding to collapse prevention level is about 90 percent. Secondly, referring to the damage index
variations-drift diagram (Fig. 3), the rate of variations of this index becomes lower from the damage index equal to 97 percent up to the end of the diagram.

The results of the mean value of the obtained damage index are shown in Table 4 for 3, 6 and 12-story frame buildings, respectively.

Table 4: Mean Value Percentage of Damage Index and Corresponding Drift for the Three, Six and Twelve-Story Frames.

<table>
<thead>
<tr>
<th></th>
<th>Three-Story Frame</th>
<th>Six-Story Frame</th>
<th>Twelve-Story Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Performance Level</td>
<td>Performance Level</td>
<td>Performance Level</td>
</tr>
<tr>
<td>DI %</td>
<td>IO</td>
<td>LS</td>
<td>CP</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>93</td>
</tr>
<tr>
<td>Drift %</td>
<td>0.80</td>
<td>1.35</td>
<td>2</td>
</tr>
</tbody>
</table>

According to the definition of damage index corresponding to equation 5, the OP level could be considered free of damage. Fig. 7 illustrates damage index variations at each performance level for the three groups of buildings.

Fig. 7: Mean value structural damage index.

According to the obtained results, the increase in the number of stories shows 25 percent reduction of damage index for the IO level, but in other performance levels and collapse level, the mean value percentage of damage index is not sensitive to the increase in stories. Therefore, relying on these results, damage index could be proposed about 18 percent at IO level, 80 percent at LS level and 90 percent at CP level for all frames. As mentioned above, damage index of the collapse point of the structure is estimated at 97 percent.

But, in FEMA 273 drifts corresponding to the OP level are introduced lower than 0.7 percent, 1 percent for IO level, 2 percent for LS level and finally 4 percent for CP level. Fig. 8 indicates that displacements expressed by the code should be reviewed for performance levels.

Fig. 8: Variations of drifts by the increase in the number of stories.
Furthermore, the presented limits in the code include all frames and the effects of number of stories are not involved. Referring to Fig. 8, it could be seen that as the height of the structure increases, displacement percentage corresponding to the damage index follows a downward trend at each performance level. Therefore, the introduced damage index could be utilized as a complement for determining structural performance levels. 

In Fig.9, drifts defined by FEMA are compared with the mean values of obtained drifts corresponding to the performance levels for all 3, 6 and 12-story frame buildings.

![Fig. 9: Comparison of drift in different performance levels with FEMA.](image)

The following three points could be extracted from this diagram. Firstly, the drift expected by the code is more than that of samples for all performance levels. Secondly, as the nonlinear phase spreads more in structures and approaches higher performance levels, the distance between the obtained drifts and standard drifts increases. Thirdly, the rise in the number of stories of the structure rapidly increases the mentioned distance.

9. Conclusion:

In this paper different methods of determining damage index are presented and their results were compared with each other. The Ghabara’s damage index was modified in terms of stiffness in order to determine structural damage extent at each performance level. In addition, the sensitivity of this index to the above sources was investigated considering uncertainty sources. According to the results, it can be concluded that damage index has the highest sensitivity to the uncertainty of geometrical properties of sections, followed by dead load in the second place. The sensitivity of damage index to yield stress and modulus of elasticity is very close to each other, both of which stand in the third place. While the sensitivity of damage index to live load stands in the last place. Reviewing results, it can be realized that the more the structure approaches the nonlinear phase and ultimately collapse point, the more the sensitivity of damage index to geometrical properties of sections increases as well as yield stress and modulus of elasticity, while the sensitivity to dead and live load parameters decreases. Results also indicate that the increase in the number of stories leads to the decrease in the sensitivity of damage index to other parameters. By increasing the number of stories, the quantity of damage index does not change significantly at different performance level, but the corresponding drift decreases by the increase in the height of the structure. The evaluation of parameters with uncertainty for different frames in this research shows that the specified drift in the codes are of higher level compared to the obtained results in this research and the codes’ expectations of structural behavior is more than their strength. This means that, in performance based design, by referring to standards in specifications the story drifts which most standards propose as a criterion for recognizing performance levels, might not satisfy its bounds while satisfying plastic rotations conditions. In such cases, modification of standards in specification, seems essential in adapting the above two criteria or developing an effective algorithm for satisfying the two mentioned conditions simultaneously. Therefore, the defined damage index can be proposed as a complement to determining code limits.

REFERENCES


