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PERFORMANCE BASED DESIGN AND DAMAGES ESTIMATION OF STEEL FRAMES WITH CONSIDERATION OF UNCERTAINTIES

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Original scientific paper
Damage levels of the structure and their corresponding displacements could be presented both qualitatively and quantitatively (based on the performance-based design method). For quantitative evaluation of seismic damage level in structures, damage index is used. Researchers have proposed several functions based on the nonlinear dynamic and cyclic behaviour 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 is introduced based on the reduced stiffness of the structure. 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. The obtained results show that the geometric characteristics of structural elements have a great influence on the sensitivity of damage index of structures. When a number of stories increase, this value and corresponding drifts will be reduced. Number of stories has an inverse influence on sensitivity.

Keywords: *damage index, performance levels, probabilistic analysis, pushover analysis, uncertainty*

Konstrukcija utemeljena na performansi i procjena oštećenja na čeličnim okvirima uzimajući u obzir nesigurnosti

Izvorni znanstveni članak
Razine oštećenja konstrukcija i odgovarajući pomaci mogu se predstaviti i kvalitativno i kvantitativno (na osnovu metode projektiranja utemeljene na performansi). Za kvantitativnu procjenu veličine štete od potresa u konstrukcijama koristi se indeks štete. Istraživači su predložili nekoliko funkcija temeljenih na nelinearnom dinamičkom i cikličkom ponašanju elemenata konstrukcije za kvantitativnu procjenu štete. S druge strane, za procjenu indeksa štete postoje razni nesigurni parametri, poput težine i otpora. U ovom se radu uvodi modificirani indeks štete zasnovan na smanjenoj krutosti konstrukcije. Rezultati modificiranog indeksa štete uspoređeni su s indeksima temeljenim na energiji i starosti konstrukcija. Rezultati pokazuju da je predloženi indeks štete odgovarajući faktor, naročito za procjenu štete kod čeličnih konstrukcija. Razmatrane su tri grupe konstrukcija, uključujući konstrukcije s 3, 6 i 12 katova kao i njihove nesigurne točke i mogući izvori. Određeni su indeks štete i pomak konstrukcije za svaki stupanj performanse. Navodi se osjetljivost indeksa štete u odnosu na parametre nesigurnosti kod svakog stupnja performanse. Nadalje, dobivena je količina štete konstrukcija s odgovarajućim pomacima. Dobiveni rezultati pokazuju da geometrijske karakteristike konstrukcijskih elemenata uveliko utječu na osjetljivost indeksa štete konstrukcija. S porastom broja katova, ta će se vrijednost kao i odgovarajući pomak, smanjiti. Broj katova obrnuto djeluje na osjetljivost.

Ključne riječi: *analiza "pushover", indeks štete, nesigurnost, probabilistička analiza (zasnovana na vjerojatnoći), stupanj performanse*

1 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 [1] and ATC 40 [2]. 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 [3]. The study of the history of these methods shows that although some of the indices 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 indices in much more complicate state. Several researches carried out in this field can be related to the works of Stephensand Yao [3], Usami and Kumar [4] and Colombo and Negro [5]. Usami and Kumar [4] developed a model for estimation of damage index capable of assigning large deformation for steel bridges. Colombo and Negro [5] proposed an index based on strength loss. The index presented by Stephensand Yao [3] is also established on dynamic response of the structure and the hysteresis 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 [1]: 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.

In Section 2, evaluation of damage index with different methods is explained. In Section 3, damage index based on the stiffness at different performance levels is considered. Section 4 is devoted to uncertainty in structures. Numerical study is introduced in Section 5. In Section 6, comparison of damage index for different frames is presented. Investigation of the sensitivity of variables at performance levels according to damage index is explained. In Section 8, suggestion for quantifying performance levels based on damage index is introduced. Future direction research is presented in Section 9 and at the end; conclusion is explained in Section 10.

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 [6] and Cosenza et al. [7]. Rodriguez [8] developed a method based on plastic energy absorption in cyclic loading. Guzman and Ishiyama [9] defined structural damages based on the rotation of structural joints in 2004 [9]. Damage index of concrete structures with regard to cracking of members was defined by Vilma et al. [10]. Another technique, the "damage index" of lateral displacement was cited in FEMA-273 [1]. This index is one the most important indices in the category of general index of the structure offered as follows [1]:

$$DI = \frac{\Delta_{\mathrm{m}}}{H}, \tag{1}$$

where Δ_{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 et al. [7], 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. Estekanchi et al. [11] defined a new relation between performance level and damage level for structures, based on the reduced stiffness. Otani and Sozen [12] 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. [13] was based on structural stiffness formulated with the following expression:

$$DI = 1 - \left(\frac{K_{\mathrm{final}}}{K_{\mathrm{initial}}} \right), \tag{2}$$

where DI is damage index, K_{initial} is initial stiffness or the initial tangent of the base shear-roof displacement curve before the earthquake impact and K_{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 represents 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 [14] considered the accumulated energy by hysteresis damping as a factor for estimating structural damages. Zhang et al. [15] 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:

$$DI = \frac{E_{\mathrm{P}} - E_{\mathrm{i}}}{E_{\mathrm{f}} - E_{\mathrm{i}}}, \tag{3}$$

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_{f}) can affect the damage index. Researchers have introduced different definitions for the collapse point of the structure [16, 17]. 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 [18, 19].

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 behaviour 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 [20, 21]:

$$DI = 1 - \frac{T_{\mathrm{e}}}{T_{\mathrm{i}}}, \tag{4}$$

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. [10] 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 behaviour 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:

$$(DI)_j = 1 - \left(\frac{K_j}{K_{\mathrm{OP}}} \right), \; j = \mathrm{OP, IO, LS, CP}; \tag{5}$$

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 Eq. (5). In order to consider and compare methods of determining damage index, structural damage extent is evaluated using Eqs. (3), (4) and (5) at four performance levels conforming to FEMA-273 [1].

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 modelling, and uncertainty in the methods of determining performance point.

In the previous researches such as Azhdaryand Shabakhty [22], 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 Tab. 1, the type of the selected probability distribution function as well as corresponding coefficient of variation of dead and live loads are presented. 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 choose uncertainty function characteristics are selected from [23, 24, 25, 26].

Table 1 Characteristics of Random Variables Selected in this Research

Sources of uncertainty	Variable	Probability distribution	Coefficient of variation
Uncertainty in loads	Dead load	Normal	0,10
	Live load	Log-Normal	0,35
Uncertainty in the strength of structural elements	Modulus of elasticity	Normal	0,05
	Yield and ultimate stress	Log-Normal	0,10
	Geometrical properties	Normal	0,04

5 Numerical study

In order to investigate behaviour of different types of buildings, we consider three types of buildings in this research, namely, 3, 6 and12-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 [27], 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 on 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 [28]), 2D frames have been used in this research. Section properties of selected members of frames are presented in Tab. 2. 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 6,5 kN/m^2 in each floor area and 6,0 kN/m^2 for roof area. The mean intensity of live load for typical floors and roof is assumed as 2,0 kN/m^2 and 1,5 kN/m^2, respectively. The difference in loads between typical floors and roof arises from different construction details for floors and roof. The structure is designed based on the tenth volume of Iranian national building regulations [29] with the loading values according to the sixth volume of Iranian national building regulations [29] and the structure is checked in accordance with the Iranian earthquake code, standard 2800 [30].

Based on the mean values of uncertainty parameters, performance point is calculated according to FEMA273 [1]. 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.

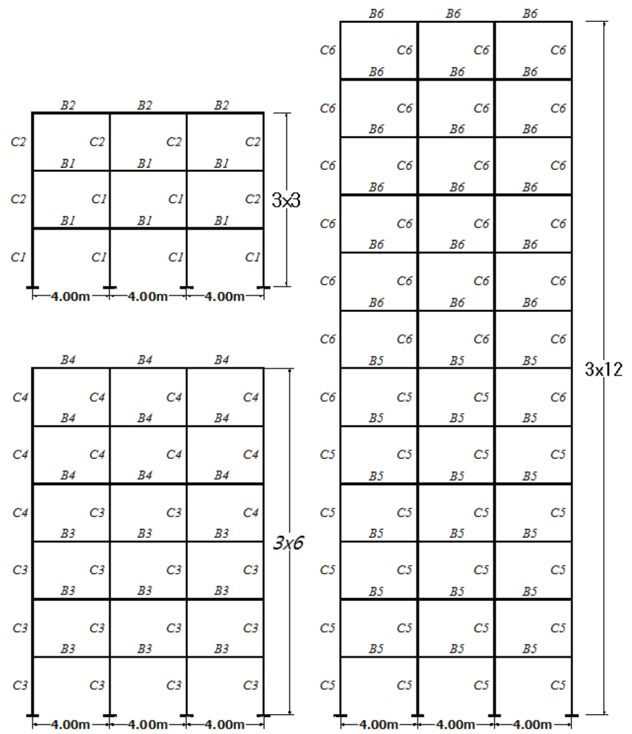

Figure 1 Investigated frame types

There is no unique reference for determining probability distribution function of variables defined in Tab. 1. It could be noted that, if the probability function is unknown, normal and lognormal functions are more common, [15 ÷ 19].

Table 2 Section Properties of Columns (C) and Beams (B)

Mean values		
	BOX 18×18×0,8	C1
	BOX 20×20×1,0	C2
	BOX 26×26×1,0	C3
	BOX 30×30×1,2	C4
E_s = 210 GPa	BOX 34×34×1,2	C5
	BOX 38×38×1,5	C6
F_y = 24 kN/cm^2	IPE27	B1
	IPE30	B2
F_u = 37 kN/cm^2	IPE33	B3
	IPE36	B4
	IPE40	B5
	IPE45	B6

Damage index represents the degree of damage that 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. As it is clear from Fig. 2, 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 % of the intact structure. This structure exhibits stiffness near 16 % 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 zone considering effects of reduced stiffness.

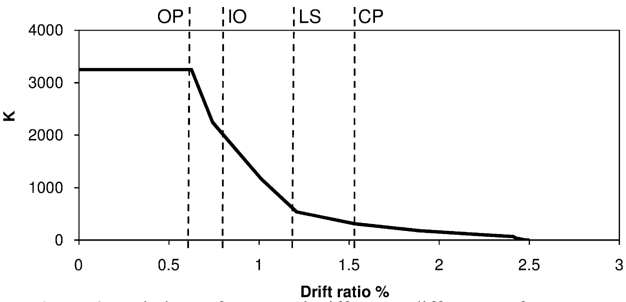

Figure 2 Variations of structural stiffness at different performance levels for six-story frame building

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 (DI_{IO}=0), at immediate occupancy level equals 30 % (DI_{OP}=0,3). It is about 83 % at life story level (DI_{LS}=0,83) and 90 % at collapse prevention level (DI_{CP}=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.

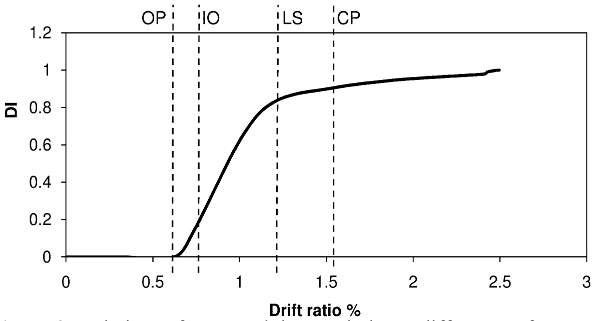

Figure 3 Variations of structural damage index at different performance levels for six-story frame building

In FEMA-273 [1], linear behaviour and drift are introduced lower than 0,7 % for the OP zone; if a structure exhibits linear behaviour with drift lower than 0,7 %, 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 behaviour 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 [1], the defined drift for the LS equals 2 percent in which the structure exhibits a nonlinear behaviour. The extracted data from Fig. 4 indicate that the obtained drift in LS zone is 1,3 %, therefore, it can be concluded that the code related expectations from structural behaviour belong to a higher level, not consistent with each other.

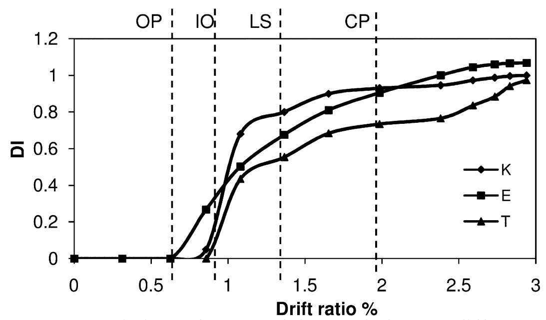

Figure 4 Variations of structural damage indexes at different performance levels in the three-story frame

The ultimate expectation and definition of the code for CP level is 4 %, while referring to the diagram, the structure is totally collapsed in 2,5 % 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 fulfilment 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 shown in Figs. 4, 5, and 6 for three 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.

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 % 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 behaviour 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. However, 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.

Evaluation of damage index based on the reduced stiffness has another advantage too. In addition to simplicity, strength reduction for each performance level is obvious, which is shown in Fig. 2 for the discussed six stories frame. Therefore, design engineer will determine required performance level with more useful information and with more certain accuracy.

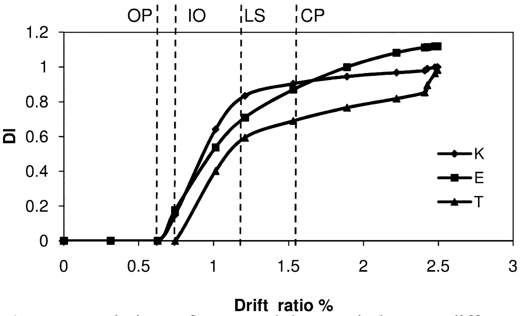

Figure 5 Variations of structural damage indexes at different performance levels of the six-story frame

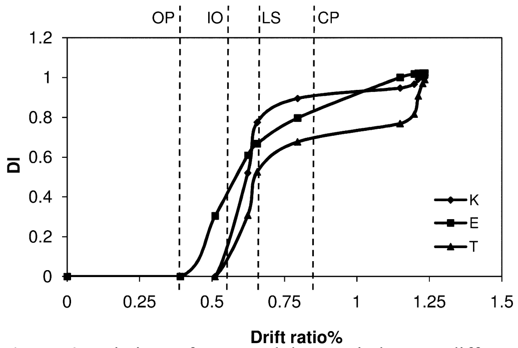

Figure 6 Variations of structural damage indexes at different performance levels of the twelve-story frame

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 Tab. 3 for the three groups of 3, 6 and 12-story frame buildings. It will be noted that the structural stiffness variations method has been used for calculating damage index.

According to Tab. 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 behaviour 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 increases, the sensitivity of geometrical properties reduces.

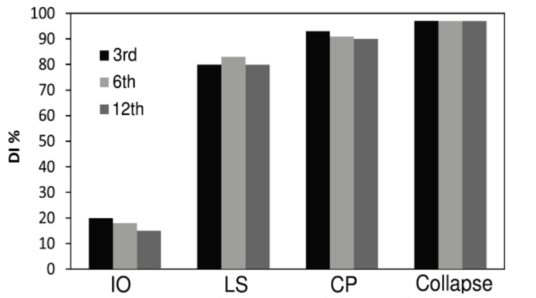

Figure 7 Mean value structural damage index

Table 3 Percentage coefficient of variations of damage index for three, six and twelve story frame buildings

	Three-story frame			Six-story frame			Twelve-story frame		
	Performance level			Performance level			Performance level		
Random variables	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
Sec. Uncertainty	16,37	16,83	17,24	10,94	11,73	14,42	7,75	8,36	9,49

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 Eq. (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 % 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 %. Secondly, referring to the damage index variations-drift diagram (Fig. 3), the rate of variations of this index becomes lower than the damage index equal to 97 % up to the end of the diagram.

The results of the mean value of the obtained damage index are shown in Tab. 4 for 3, 6 and 12-story frame buildings, respectively. According to the definition of damage index corresponding to Eq. (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. According to the obtained results, the increase in the number of stories shows 25 % 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 % at IO level, 80 % at LS level and 90 % at CP level for all frames. As mentioned above, damage index of the collapse point of the structure is estimated at 97 %.

Table 4 Mean value percentage of damage index and corresponding drift for the three, six and twelve-story frames

Mean value	Three-story frame				Six-story frame				Twelve-story frame			
	Performance level				Performance level				Performance level			
	IO	LS	CP	Collapse	IO	LS	CP	Collapse	IO	LS	CP	Collapse
DI %	20	80	93	97	18	83	91	97	15	80	90	97
Drift R %	0,80	1,35	2	2,5	0,65	1,2	1,6	2,3	0,6	0,7	0,85	1,2

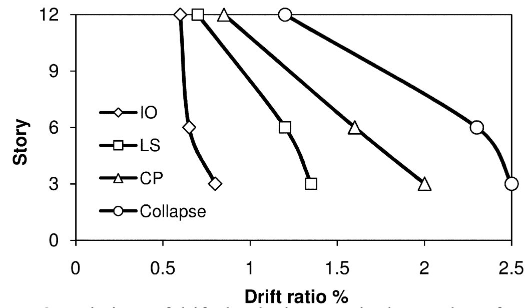

Figure 8 Variations of drifts by the increase in the number of stories

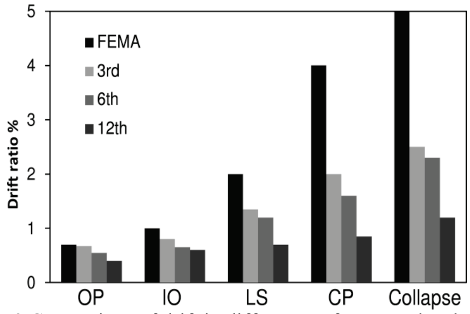

Figure 9 Comparison of drift in different performance levels with FEMA

But, in FEMA 273 [1] drifts corresponding to the OP level are introduced lower than 0,7 %, 1 % for IO level, 2 percent for LS level and finally 4 % for CP level. Fig. 8 indicates that displacements expressed by the code should be reviewed for performance levels. 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. 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 Ghobara'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 the 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 is of a higher level compared to the obtained results in this research and the codes' expectations of structural behaviour are 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.

Damage index defined based on the reduced stiffness, has a direct relation to other variable parameters which are discussed in this paper. Therefore, sensitivity of parameters like drifts and joint rotations have a direct influence on the mentioned damage index. When the level IO is the objective level, parameters like member's geometry and dead load are in priority, and when the level LS is the objective level, parameters like member's geometry, allowable stress and modulus of elasticity are in priority.

In this paper, methods for determining damage index with emphasis on the corrected reduced stiffness method, are compared with each other. Probability analysis and uncertainty were considered in the analysis process. Above mentioned research could be done for other steel frames like the braced ones, by interested researchers. In order to evaluate reliability of structures for different performance levels, damage index of each level should be related to reliability of structure. Performance based design is a good substitution instead of strength based design. Advantages and disadvantages of proposed method could be defined based on the above mentioned process. Furthermore, applying optimization in the analysis process will increase accuracy of the obtained results.

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