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Modified Damage Index Calculation Method for Frame-Shear Wall Building Considering Multiple Demand Parameters

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ABSTRACT

In this study, multiple objectives on earthquake damage assessment procedures have been investigated. The Unified performance-based design (UPBD) method has been used to design the Reinforced Concrete (RC) frame shear wall building. First, the Damage index (DI) of the building has been estimated by using Park and Ang method. It has been found that this method is highly time-consuming. Hence, it is not found suitable for large scale investigation. Therefore, a new approach has been suggested to reduce the computational time and efforts in the case of complex structures in evaluating the global damage index (GDI). In this present study, the most three influencing parameters of the building have been considered to find the GDI. It has also been observed that the most damage occurs on the ground storey of the building. The suggested method efficiently calculates a reliable GDI that can assess building damage from small to large scale buildings.

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NOMENCLATURE

DI	Damage Index	GM	Ground Motion
MDOF	Multi-degree of freedom	h_b	Beam depth
SDOF	Single degree of freedom	θ_{pb}	Allowable plastic rotation of the beam
UPBD	Unified performance-based design	Δ_d	Design displacement
SCGM	Spectrum compatible ground motions	m_e	Effective mass
GDI	Global damage index	h_e	Equivalent heigh
EDPs	Engineering Demand Parameters	m_i	Mass of *i-th* storey
LDI or SDI	Local or storey wise damage index	Δ_{iyw}	Yield displacements of the wall in *i*-th storey
DDBD	Direct displacement-based design	Δ_i	Profile displacement
ESDOF	Equivalent single degree of freedom	N	Number of the storey
SCGM	Spectrum compatible ground motions	μ_w	Displacement ductility of the wall
LSPL	Life safety performance level	$\Delta_{he,y}$,	Yield displacement of the wall
θ_{yw}	Yield rotation of the wall	M_w	Wall moment
θ_{pw}	Plastic rotation of the wall	ξ_w	Wall damping moment
θ_{yw}	Yield rotation of the wall	$M_{ot,f}$,	Frame overturning moment
ϕ_{yw}	Yield curvature	ξ_f	Frame damping
h_{inf}	Inflection height	$T_{e,trial}$	Trial effective time period
ε_y	Yield strain of rebar	r	Post-yield stiffness ratio
L_w	The horizontal length of the wall	K_e	Effective stiffness
t_w	The thickness of the wall	V_b	Base shear
τ_c	Permissible shear stress of concrete	δ_M	Optimum deformation under earthquake loading
DL, LL, F_x, F_y	Dead load, live load, seismic load in the *x*-Direction and y-direction	δ_u	Optimum deformation monotonic loading
β	Non-negative parameter	Q_y	Yield strength,

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θ_d	Design drift	dE	Hysteresis energy
η	Reduction factor corresponding to the damping	d_{max}	Optimum roof displacement
θ_{yw}	Yield rotation of the wall	ϕ_{yw}	Yield curvature of wall
V_{Wall}	Shear carried by the walls	F_i	Force applied in the *i-th* floor level
D_{Story}	Storey wise damage index	C	Regression constant
$E_{storey,i}$	Hysteretic energy dissipated of i^{th} storey	E_i	Hysteretic energy dissipated of i^{th} member
D_i	*DI* of i^{th} member	n	Number of members in a particular storey
D_{global}	*DI* of the entire structure	t_w	Thickness of the wall

1. INTRODUCTION

Structures get damaged and often collapse under high intensity of earthquakes. The Damage Index (DI) is a parameter that can be used to quantify the amount of damage suffered by the structure. Damage is the process of deterioration of a structure's strength, ductility and stiffness, and that is why estimation of damage index is very important. Structural design should be done to minimize the damage. Reinforced concrete (RC) frame shear wall buildings are mainly used for residential, commercial and office buildings. This type of buildings is efficient in resisting earthquake loads. But still, there can be damage to such buildings leading to severe economic losses [1-3]. Several approaches are available for evaluating DI and have been proposed by numerous researchers [4-8]. Park and Ang [9] considered only two parameters to determine the DI of the structures, namely, maximum deformation and hysteretic energy. The limitations have been highlighted in determining DI of the buildings considering the displacement mode shapes, have been identified experimentally. Yazdannejad and Yazdani [10] have improved the Park and Ang damage model by adding stiffness using Bayesian framework. Hait et. al [11] have considered U-, L- and rectangular-shaped RC frame buildings and found rectangular-shaped buildings are least vulnerable to damage. From Several studies based on DI, it has been observed that, there are many approaches available for evaluating DI, but those are either incomplete or tedious to use. Likewise, Park and Ang's approach is tedious and time-consuming. Estimation of the DI by adding multiple parameters that define the buildings real damage state under seismic excitation may lead to more accurate results.

In the present study, an 8-storey RC frame-shear wall building of Life Safety performance level has been considered for the assessment of DI. The unified performance-based design (UPBD) method has been employed for designing the RC frame shear wall building. Nonlinear time history analysis (NLTHA) is performed under spectrum compatible ground motions (SCGM) as per EC-8 demand spectrum at 0.45g level and type B soil. In this study, the 3 most influential parameters have been considered to determine the building's global damage index (GDI). Here, a relationship between Park and Ang DI and Engineering Demand Parameters (EDPs) has been developed to increase the ease of finding the DI of the buildings.

2. DAMAGE INDEX

The damage index (DI) is a criterion that measures the amount of damage in a structure for a specified hazard level. These damage indices of the structures are expressed by different response parameters obtained from analytical assessment. Researchers have proposed several methods on DI, but most of them have considered limited EDPs; therefore, it could not give accurate results of the DI of the structures. To compute the DI of the structure, there is a need to assume more EDPs to get accurate results. DI is classified into two ways: local or storey wise damage index (LDI or SDI) and GDI, and the brief description reported in literature [12].

3. DESIGN PHILOSOPHY USED

Sullivan et al. [13] established the direct displacement-based design (DDBD) method for dual frame buildings. In this method, interstorey drift was the only target design parameter considered as well as the member sizes are also decided by trial and error process. In contrast, in the UPBD method, two target design criteria, namely, drift and performance level (in terms of plastic rotation) can be satisfied. This method also gives member size at the beginning of design process which avoids iteration. Choudhury and Singh [14] introduced the UPBD method for RC Frame buildings and UPBD method for frame-shear wall building has been reported by Mibang and Choudhury [15]. In the design process the multiple degrees of freedom (MDOF) structure is represented by an equivalent single degree of freedom (ESDOF) system as shown in Figure 1. For the benefit of readers, the basics of UPBD method for frame-shear wall building are discussed here in brief. The drift rotation of the building consists of yield rotation and plastic rotation of the wall. As per Figure 1, Equation (1) is obtained.

$$\theta_d = \theta_{yw} + \theta_{pw} \tag{1}$$

The yield rotation of the wall and yield curvature of the wall can be determined by Equations (2) and (3), respectively.

$$\theta_{yw} = \phi_{yw} \frac{h_{inf}}{2} \tag{2}$$

$$\phi_{yw} = \frac{2\varepsilon_y}{L_w} \tag{3}$$

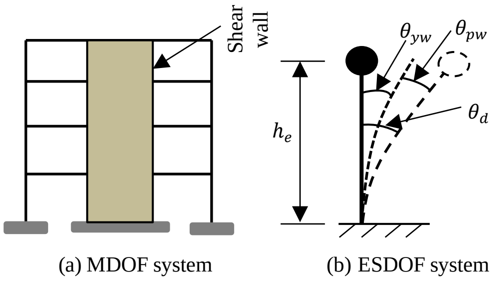


Figure 1. MDOF and ESDOF systems

Using Equations (1), (2) and (3), Equation (4) is obtained.

$$L_w = \frac{\varepsilon_y h_{inf}}{\theta_d - \theta_{pw}} \tag{4}$$

The thickness of the wall (t_w) is obtained from Equation (5).

$$t_w = \frac{V_{Wall}}{0.8 \times L_w \times \tau_c \times N_w} \tag{5}$$

Factor 0.8 is used to reflect the fact that 80% of the wall length is considered effective in taking shear (IS 456 2000). The beam depth can be determined by Equation (6).

$$h_b = \frac{0.5\varepsilon_y l_b}{\theta_d - \theta_{pb}} \tag{6}$$

The width of the beam is taken as 1/4th to 1/3th of beam depth as per common practice. The h_{inf} is a parameter of dual system design, and it can be found out by determining the moments that are borne by frame and shear wall.

The yield displacement profile of the wall is obtained using Equations (7).

$$\Delta_{iyw} = \frac{\emptyset_{yw} h_i h_{inf}}{2} - \frac{\emptyset_{yw} h_{inf}^2}{6}, \text{ when} h_i \geq h_{inf} \tag{7a}$$

$$\Delta_{iyw} = \frac{\emptyset_{yw} h_i^2}{2} - \frac{\emptyset_{yw} h_i^3}{6 h_{inf}}, \text{ when } h_i \leq h_{inf} \tag{7b}$$

$$\emptyset_{yw} = \frac{2\varepsilon_y}{L_w} \tag{7c}$$

Design displacement profile is obtained from Equation (8)

$$\Delta_i = \Delta_{iyw} + \left(\theta_d - \phi_{yw} h_{inf}/2\right) h_i \tag{8}$$

The MDOF building is converted to an ESDOF and the properties of ESDOF system are determined by using Equations (9) to (11).

$$\Delta_d = \frac{\sum_{i=1}^{n} m_i \Delta_i^2}{\sum_{i=1}^{n} m_i \Delta_i} \tag{9}$$

$$m_e = \frac{\sum_{i=1}^{n} m_i \Delta_i}{\Delta_d} \tag{10}$$

$$h_e = \frac{\sum_{i=1}^{n} m_i \Delta_i h_i}{\sum_{i=1}^{n} m_i \Delta_i} \tag{11}$$

Wall ductility demand is determined by Equation (12).

$$\mu_w = \frac{\Delta d}{\Delta_{he,y}} \tag{12}$$

Frame ductility is determined by Equations (13) and (14).

$$\mu_f = \left(\frac{\Delta_i - \Delta_{i-1}}{h_i - h_{i-1}}\right) \frac{1}{\theta_{yf}} \tag{13}$$

$$\theta_{yf} = \frac{0.5 l_b \varepsilon_y}{h_b} \tag{14}$$

The trial value of the effective period is obtained from Equations (15) and (16).

$$T_{e,trial} = \frac{N}{6}\sqrt{\mu_{sys}} \tag{15}$$

$$\mu_{sys} = \frac{M_w \mu_w + M_{ot,f} \times \mu_f}{M_w + M_{ot,f}} \tag{16}$$

The frame equivalent viscous damping and the wall equivalent viscous damping components are calculated using Equations (17) to (19).

$$\xi_w = \frac{95}{1.3\pi}\left(1 - \mu_w^{-0.5} - 0.1 \times r \times \mu_w\right)\left(\frac{1}{\left(T_{e,trial} + 0.85\right)^4}\right) \tag{17}$$

$$\xi_f = \frac{120}{1.3\pi}\left(1 - \mu_w^{-0.5} - 0.1 \times r \times \mu_f\right)\left(1 + \frac{1}{\left(T_{e,trial} + 0.85\right)^4}\right) \tag{18}$$

$$\xi_{SDoF} = \frac{M_w \xi_w + M_{ot,f}\, \xi_f}{M_w + M_{ot,f}} \tag{19}$$

Displacement spectra corresponding to design spectra are drawn for various dampings. For this purpose, Equation (20) is utilized. Displacement spectra corresponding to EC-8 design spectra for soil type B and at 0.45g level have been used in the present study and are shown in Figure 2.

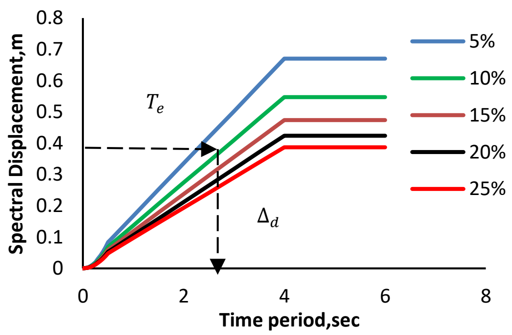


Figure 2. Displacement Spectra corresponding to EC-8 design spectra for soil type B at 0.45g level

$$\eta = \sqrt{\frac{10}{(5+\xi_{ESDOF})}} \geq 0.55 \quad (20)$$

Effective stiffness (K_e) is give by Equation (21).

$$K_e = \frac{4\pi^2 m_e}{T_e^2} \quad (21)$$

Base shear (V_b) is given by Equation (22).

$$V_b = k_e \Delta_d \quad (22)$$

The computed base shear is distributed to different floors as per Equation (23).

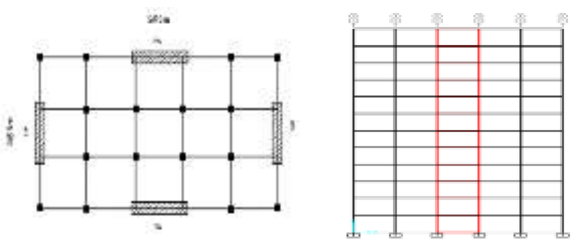
$$F_i = V_b \frac{m_i \Delta_i}{\sum_{i=1}^{n} m_i \Delta_i} \quad (23)$$

Where, F_i is the force applied in the *i*-th floor level of the building.
The combinations of load used for design are:
$DL + LL$
$DL + LL \pm F_x$
$DL + LL \pm F_y$
Design is done using the expected strength of materials [16]. The capacity design has to be done so that the column to beam capacity ratio is more than 1.4 according to 13920:2016.

3. DESIGN OF REPRESENTATIVE BUILDING

3. 1. Model Selection

In the present study, an 8-storey frame-shear wall building has been considered. The plan and elevation of the building are shown in Figure 3. The building has been designed using the UPBD method for target performance objective of LS performance level and 2% drift. The sizes of beams and columns are given in Table 1. The material specifications are given in Table 2. NLTHA is performed under five spectrum compatible ground motions (SCGM) as per EC-8 [17] demand spectrum at 0.45g level and type B soil condition. The SCGMs are generated using software of Kumar [18]. The details regarding SCGMs have been given in Table 3. The match of response spectra out of SCGMs with the EC-8 demand spectrum is shown in Figure 4. Finite element software SAP2000 v. 21 [19] has been used to model, design, and analyze the building. The storey height is kept constant to 3.1 m.



(a) Plan (b) Frame elevation

Figure 3. Building model considered in the study (a) Plan (b) elevation [SW indicates shear wall]

TABLE 1. Sizes of members in the building considered (mm)

Building name	Inner Column (mm)	Outer column storey-wise (mm)	Beam size (mm)	Shear wall thickness (mm)	Length of wall (mm)
B-8-LS	700×700	800×800 (1-4) 750×750 (5-6) 700×700 (7-8)	700×450	150	5000

TABLE 2. Material properties related to concrete and rebar

Materials properties	Unit	Values
concrete compressive strength (*fck*)	MPa	30
steel yield strength (*fy*)	MPa	500
Modulus of elasticity of concrete (*Ec*)	MPa	$5000\sqrt{fck}$
Modulus of elasticity of steel (*Es*)	MPa	200000
Poisson's ratio (steel)	-	0.3
Poisson's ratio (concrete)	-	0.15

TABLE 3. Details of SCGMs used

Sl.No.	Name	Background Equation (India)	Year of occurrence	Durations in sec
1	GM1	Baithalangso	1988	78.05
2	GM2	Nonghklaw	1986	29.54
3	GM3	Silchar	1988	46.81
4	GM4	Umsning	1981	70.52
5	GM5	Barkot	1991	31.61

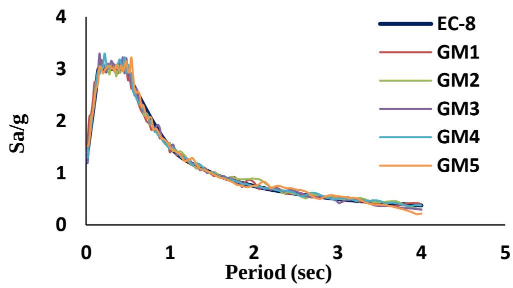


Figure 4. Match of response spectra of SCGMs with EC-8 design spectrum

4. DI OF STRUCTURE

In recent years, several DI models have been introduced by many researchers to predict the structural damage. Among all the methods, Park and Ang is the most common and popular approach (Equation (24)) used by other researchers. It also gave the expression for the local damage index (LDI) (Equation (25)) as well as global damage index (GDI) (Equation (26)). Nevertheless, this method is very time-taking in calculating the GDI.

Therefore, there is a need for some method which can provide ease in finding the GDI of structure.

$$DI = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE \quad (24)$$

Storey DI and Entire storey DI are evaluated using Equations (24) and (25).

$$SDI = \frac{\sum_{i=1}^{n} D_i E_i}{\sum_{i=1}^{n} E_i} \quad (25)$$

$$GDI = \frac{\sum_{storey,i=1}^{n} D_{storey,i} E_{storey,i}}{\sum_{storey,i=1}^{n} E_{storey,i}} \quad (26)$$

5. 1. Procedure Followed for the Proposed DI Assessment In the literature review, it has been found that limited work had been carried out considering multiple EDPs for calculating the DI of the buildings. In this study, multiple EDPs have been considered for calculating the DI, and these parameters have been combined in a mathematical expression to find the DI of the building. Out of four engineering demand parameters, 3 parameters have been found to be the most influential EDPs for the building. To determine the most significant parameters among the four EDPs, a correlation matrix has been prepared. The top three influencing EDPs are selected from the correlation matrix, as shown in Table 4. The corresponding $R^2 > 90\%$ is maximum, and hence it can be considered the most influencing parameter variable on DI.

By combining the 3 most influential parameters, a new expression can be proposed for finding the DI of the building, and a correlation has been established by linear regression analysis (LRA) between Park and Ang global DI and EDPs. The proposed DI expression is shown in Equation (27).

$$GDI = 0.083 \times \text{IDR} + 0.088 \times \theta + 0.682 \times d_{max} + 0.242 \quad (27)$$

Equation (27) has been generated from the considered EDPs, which were evaluated by considering 10 data points from the simulated model. The flow chart of the proposed method is shown in Figure 5.

TABLE 4. Correlation matrix for selected EDPs to categorize the most suitable variables

	GDI	IDR	Joint Rotation	Roof Displacement	Hysteresis Energy
GDI	1.0	0.962	0.959	0.954	0.500
IDR	0.962	1.0	**0.969**	**0.950**	0.479
Joint Rotation	0.959	0.969	1.0	**0.943**	0.443
Roof Displacement	0.954	0.950	0.943	1.0	0.572
Hysteresis Energy	0.500	0.479	0.443	0.572	1.0

In this study, ground storey experiences the maximum damage; therefore, the contribution of the ground storey is maximum in GDI. Comparing the GDI and the ground storey damage, it has been found that 0.819 times of ground storey DI displays equivalent GDI with an accuracy level of 92% (R^2=0.92). The expression is given by Equation (28). This method can be used only when the ground storey damage is known.

GDI= 0.819× DI of the ground storey (28)

The damage index (DI) by using 3 individual response parameters is expressed by Equation (29).

$$\begin{aligned} \text{DI} &= 0.1539 \times \text{IDR} + 0.243 \text{ for IDR} \\ \text{DI} &= 4.6703 \times \Theta + 0.4367 \text{ for } \Theta \\ \text{DI} &= 1.3729 \times d_{max} - 0.2556 \text{ for } d_{max} \end{aligned} \quad (29)$$

5. RESULTS AND DISCUSSIONS

In this study, an NLTHA has been performed to determine the actual response in each step of the building. Park and Ang DI approach is very time-taking as well as consuming lots of time with the increase of the height of the building. Thus, the author attempted to establish a connection between Park and Ang method and calculated EDPs GDI of structure. Finally, the proposed method, i.e. calculated EDPs GDI, is compared with Park and Ang GDI method and shown in Figure 7. To validates the proposed method, another building with a different storey height (H=3.3m) has been analyzed, and GDI has been evaluated. It has been found that after changing the height of the floor of the building, the proposed approach is also capable of assessing the DI same way like Park and Ang GDI shown in Figure 6, and it proves that the proposed method gives approximate same results as the park and Ang GDI method.

The proposed method calculates GDI almost same as park and Ang method (R^2 =0.95) as shown in Figure 7. The estimated slope of the proposed method (eqution 27) is 0.945 which shows good correlation between these two methods.

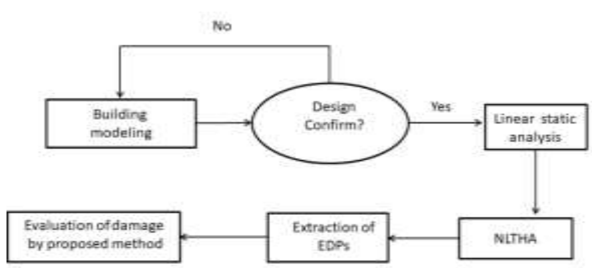


Figure 5. Flow chart followed by the proposed method

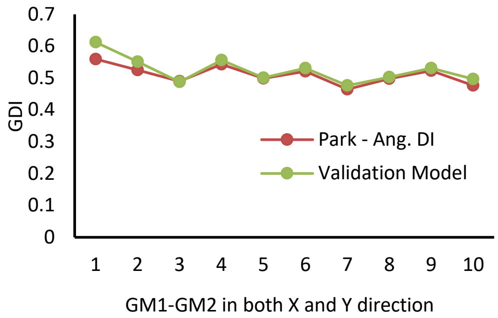


Figure 6. Comparison between Park and Ang. and proposed (Equation (27)) GDI

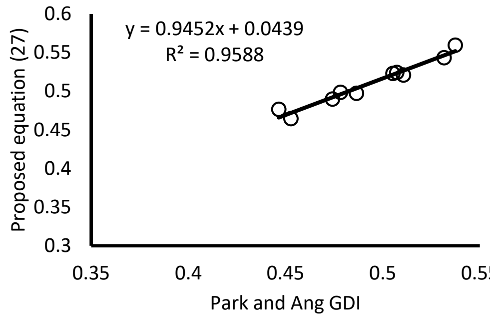
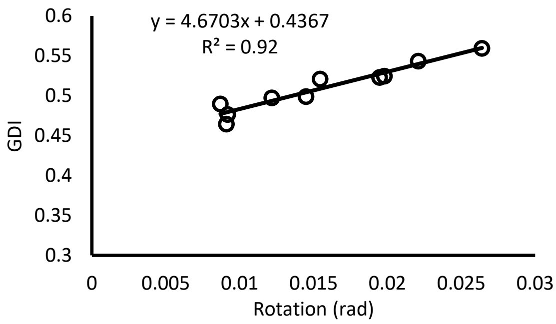


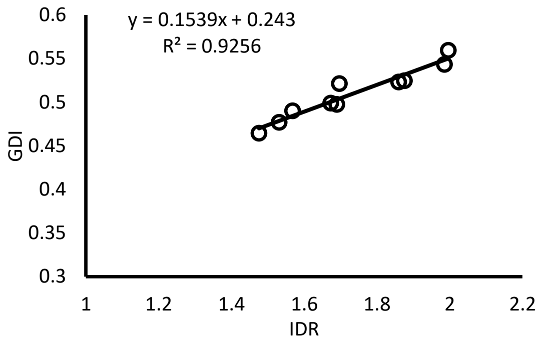
Figure 7. The fit of the Park-Ang GDI with the proposed GDI (Equation 27)

Figure 8 shows a connection between Park and Ang DI and individual EDPs. This method decreases the computational time and would fit the investigation of large-scale damage index (DI).

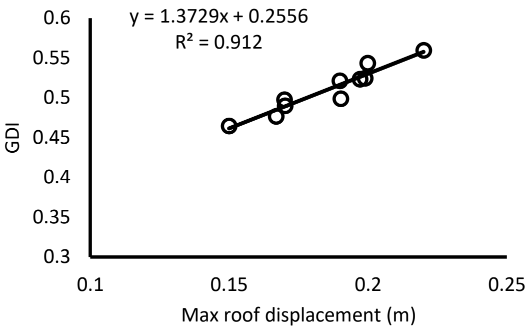
It is observed from Figures 9 and 10 that the calculated values of DI are highest at the ground storey level. Therefore, the contribution of the ground storey is maximum to GDI. A suitable correlation between ground Storey damage and GDI, has been found from the current study (Equation (28)). Therefore, GDI to ground storey DI ratio is 0.819. Likewise, the ratios for other floors can be obtained. Actual GDI versus empirical GDI (Equation (28)) is plotted in Figure 11 and it shows that there is a high accuracy rate of the empirical formula, which is greater than 92%.



(a)



(b)



(c)

Figure 8. The comparison presented between individual EDPs and Park-Ang. DI a) Rotation versus GDI, b) IDR versus GDI, c) Max roof disp. versus GDI

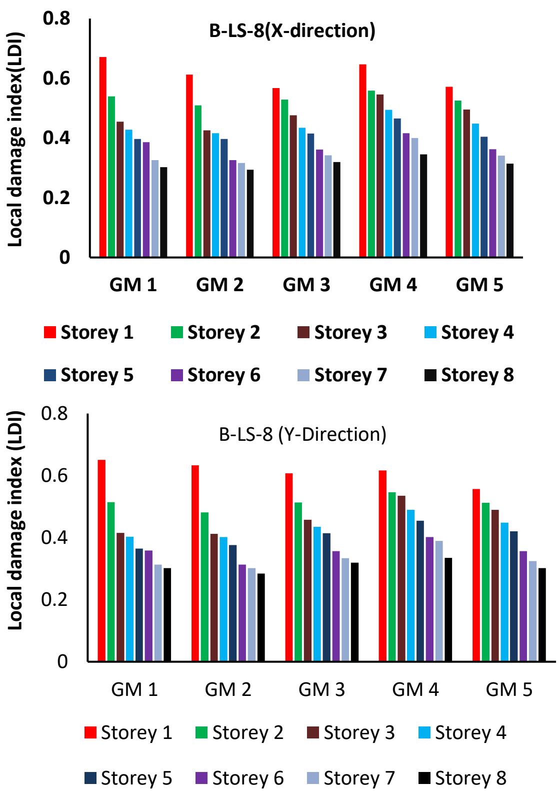


Figure 9. Storey-wise damage index (LDI) is shown for five ground motions in both X and Y directions

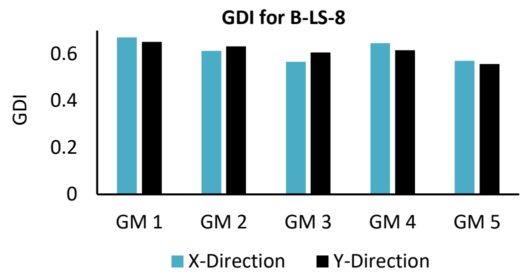


Figure 10. Park and Ang. Global damage index of an 8-storey building in both the X-Y directions

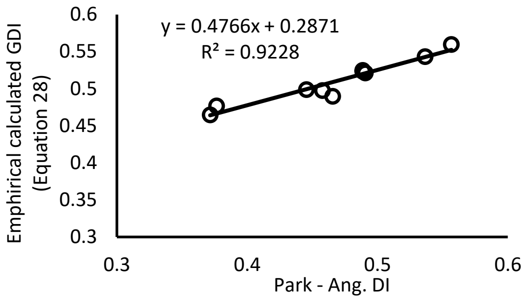


Figure 11. Empirically calculated GDI (from Equation 28) versus Park and Ang DI

5. CONCLUSION

In this study, 3 different expressions are proposed for the assessment of the DI of RC frame-shear wall building. The proposed approach considers maximum roof displacement, IDR, and joint rotation as EDPs. The reason behind proposing a new approach is to reduce the computational time as well as effort. The new proposed equation is simple, accurate, and easy to apply. The outcome of the current research shows that the proposed equation (Equation 27) simplifies the Park and Ang approach. Therefore, this proposed approach is suitable for evaluating the DI of the building from a small to large scale. Also, Equation (28) can be used for evaluating the DI of buildings but this equation can be used only after finding storey wise DI. Equation (29) can also be used for finding the GDI of the building, but the level of accuracy is lesser than both the proposed equation (Equations. 27 and 28). According to the correlation matrix shown in Table 1, where 4 engineering demand parameters has been chosen, and it has been found that 3 parameters (i.e. joint rotation, optimum roof displacement, and Inter storey drift ratio) are found as the most influential parameters with the accuracy rate of 95% ($R^2 = 0.95$ with GDI). As a result, this proposed approach can be used to find the GDI of a structure to achieve a high degree of accuracy. It has been found that the maximum damage occurs at the lower storey of the building; therefore, the ground storey should be designed with special care.

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Persian Abstract

چکیده

در این مطالعه ، اهداف متعددی در مورد روش های ارزیابی خسارت زلزله مورد بررسی قرار گرفته است. روش طراحی متحرک مبتنی بر عملکرد (UPBD)برای طراحی ساختمان دیوار برشی قاب بتنی مسلح (RC)استفاده شده است. ابتدا ، شاخص آسیب (DI)ساختمان با استفاده از روش پارک و انگ برآورد شده است. مشخص شده است که این روش بسیار وقت گیر است. بنابراین ، برای تحقیقات در مقیاس بزرگ مناسب نیست. بنابراین ، یک روش جدید برای کاهش زمان محاسبه و تلاش در مورد ساختارهای پیچیده در ارزیابی شاخص خسارت جهانی (GDI)پیشنهاد شده است. در این مطالعه حاضر ، سه پارامتر تأثیرگذار ساختمان برای یافتن GDI در نظر گرفته شده است. همچنین مشاهده شده است که بیشترین آسیب در طبقه همکف ساختمان رخ می دهد. روش پیشنهادی یک GDI قابل اعتماد را محاسبه می کند که می تواند آسیب ساختمان را از ساختمانهای کوچک تا بزرگ ارزیابی کند.