International Journal of Engineering

Journal Homepage: www.ije.ir

RESEARCH NOTE

Damage Assessment of Reinforced Concrete Buildings Considering Irregularities

P. Hait*, A. Sil, S. Choudhury

Civil Engineering Department, National Institute of Technology Silchar, Assam, India

PAPER INFO

Paper history:
Received 7 June 2019
Received in revised form 28 August 2019
Accepted 12 September 2019

Keywords:
Damage Assessment
Engineering Demand Parameter
Local and Global Damage Index
Non-linear Time History Analysis
Reinforced Concrete Framed Building

ABSTRACT

Structural damage can be controlled in performance based seismic design (PBSD) according to the requirement under a certain hazard level. During strong ground motion (GM) such buildings suffer minor to major damages depending on the shaking level of GM. The available damage assessment methods are complex, tedious and time-consuming procedure. In the present study, a simplified empirical model has been proposed that computes the GDI in a single step using the engineering demand parameters (EDPs) namely joint rotation, Inter storey drift (IDR), peak roof displacement. It has been found that the proposed method gives results of GDI near to Park-Ang model. It has been observed that the ground storey suffers maximum damage for all cases. Further, a relationship has been established between ground story DI and global DI. The proposed model effectively estimates reliable DI and could be used as a powerful tool for estimating seismic damage in buildings, especially for massive structures.

doi*: 10.5829/ije.2019.32.10a.08*

1. INTRODUCTION

The PBSD is one of the best design philosophies where performance level is predefined by the designers according to the demand and importance of the structures under certain hazard level. Structural damage is a required quantity to achieve the desired performance level. Structural damage mainly occurs due to degradation of strength, stiffness or ductility. Damage index (DI) of structures evaluated using different methods previously by researchers for reinforced concrete (RC) component, to determine DI in terms of maximum deformation and cyclic loading effect [1, 2]. Further, DI was presented in single or a combination of double parameters like IDR, joint rotation, stiffness and hysteretic energy [3-5]. Park-Ang DI updated in 2006 introducing three-dimensional damage index [6] accounting bi-directional and torsional responses. Ductility based damage index [7], empirical mode decomposition and fast Fourier integration [8] introduced and applied in RC frame, where it was determined considering pushover curve before and after the occurrence of the earthquake [9]. In this context, a comprehensive review [10, 11] has been published by the authors on local and global damage index (LDI and GDI) of both bridges and building along with their mathematical expressions. In the overview seismic zonal (IS: 1893-2016) based damage assessment [12] had been explained for RC buildings with different structural configurations for reliable damage assessment of structures to make the study robust.

From extensive literature review, it can be mentioned that several damage assessment methods suggested by researchers till date, but those methods are complex, inefficient or considers only one or two response parameters and are unable to capture the seismic degradation characteristics of a structure individually. The drawback of these methods is they are unable to capture actual damage state of the structures efficiently.

To estimate DI of the structures like RC, steel and timber, Park-Ang method was the preferred choice till date. Estimation of Park-Ang GDI for Multi-degree freedom system (MDOF) involves tedious calculation and takes huge computational time to obtain reliable results [10, 11]. In this research, a relationship between Park-Ang damage index and EDPs has been established and presented to simplify the damage assessment

*Corresponding Author Email: *pritamhait15@gmail.com* (P. Hait)

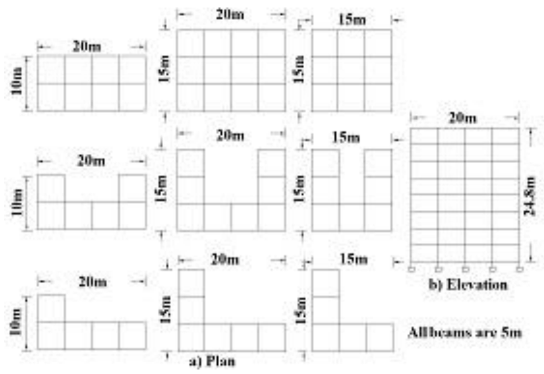


Figure 1. Plan and elevation of the buildings

method. The proposed approach is unique and applied on 8 storey building. The diversity of application of this approach makes it acceptable in wide way including regular and irregular low-rise, mid-rise and high-rise buildings. This paper shows a unique simplified approach to assess structural damage of a massive structure within a small time frame.

2. DAMAGE INDEX OF STRUCTURE

The degree of destructiveness of structure is called damage index. However, up to till date a limited research work has been published to estimate DI considering multiple demand parameters. Therefore, extensive research is required to unfold the actual damage characteristics and the parameters which are involved in structural damage directly. A typical classification of DI (Tabeshpour et al. 2004) is shown in supplementary Figure 1.

3. EXAMPLE MODEL

3. 1. Study Region The North-East and Himalayan belt are the most earthquake-prone region in India. Different types of structures such as reinforced cement concrete (RCC), steel, timber, composite, and Assam type housing are constructed here and functioning as a residential and commercial building. They are prone to high seismic hazard. More than hundreds of earthquake occurred in the past such as the Assam earthquake (1950) and Shillong earthquake (1897) in this region. An extensive investigation is essential to explore the seismic behavior of such structures considering its storey level in this seismic zone.

3. 2. Model Selection To examine and understand the configuration complexity effecting in mid-rise structures, an eight-storey RC framed building (storey height = 3.1m) with rectangular shaped, L shaped and U shaped with different of plan aspect ratio (PAR) 0.5, 0.75 and 1 (Figure 1) for each case have been considered. The nomenclature of all models is given in supplementary Table 1. Cross-section of beams and columns in the different floor is shown in supplementary Table 2. At bottom seismic demand is higher than the upper storey; therefore, the column cross-section is higher in the bottom storey and it decreases with increasing of storey level. Material properties are given in supplementary Table 3.

3. 3. Ground Motion Selection The northeast (NE) of India belongs to seismic zone-V, which is the most seismic vulnerable region in the country where hazard and risk are very high. In this seismic region, thousands of structures are in a vulnerable condition and may collapse during a future seismic event. Hence, in this research, the authors have emphasized to study such kind of RC structural characteristics in this zonal intensity level i.e. 0.36g as per Indian seismic code IS:1893-2016. To study the non-linear behavior of the structure, seven pair of real recorded (Table 1 and Figure 2) spectrum compatible ground motions (SCGM) were selected from NE region India considering different magnitudes (Mw 4.5-6.9), frequency and duration of earthquakes occurred to consider the effects of all site specific ground motion characteristics essentially in near and far field motion behaviour on structures to consider the real attributes.

TABLE 1. Seven site specific recorded ground motions

Sl. No.	Name of EQ	Moment magnitude (M_w)	EQ Stations	Ground motion Characteristics			Hypo-central dist. (km)
				Frequency (Hz)	PGA (m/s^2)	Duration (s)	
1	NE India (1986)	4.5	Ummulong	2	1.455	16.94	44.9
2	India Burma Border, India (1988)	6.9	Diphu	1.92	1.386	81.75	210.1
3	India Burma Border, India (1997)	5.5	Jellalpur	3.12	1.18	25.6	41.9
4	Uttarkashi, India (1991)	6.7	Uttarkashi	2	1.005	36.16	21.7
5	India Burma Border (1988)	6.9	Berlongfer	4.54	1.074	119.7	220.1
6	India-Burma Border, (1995)	6.4	Halflong	3.12	1.03	12.94	261.9
7	India-Burma Border, (1990)	5.9	Laisong	2.63	1.12	9.04	233.5

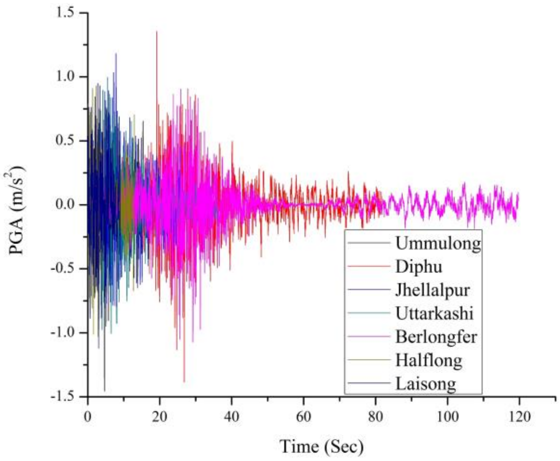


Figure 2. Seven pair of real recorded ground motions

3. 4. Analysis and Design of the Building All beams are allowed to fail (or reach to form plastic hinges) before column to prevent catastrophic failure. This capacity design phenomenon was followed to design the buildings. RCC design was done as per IS 456-2000 [13] and seismic design was done by response spectrum method as per IS 1893-2016 [14] where column/beam capacity ratio is greater than 1.4 as per 13920-2016 [15] to follow strong column-weak beam principle. Non-linear static pushover analysis has been performed to check the capacity of the building in both X and Y directions. Non-linear time history analysis (NLTHA) was performed in SAP2000v15 under seven pair of different site-specific real earthquake spectrum compatible ground motion (Table 1 and Figure 2) in both X and Y directions.

4. METHODOLOGY

4. 1. Non-Linear Model To analyse the buildings NLTHA has adopted to reflect the realistic elasto-plastic behaviour under earthquake excitation. The framed buildings were modelled nonlinearly as per FEMA 356 [16]. Force-deformation behavior for a typical flexural hinge is shown in supplementary Figure 2. For the beams M_3 hinge and for column P-M_2-M_3 hinge interaction was assigned as per FEMA356-2000 (Tables 6 and 7 in FEMA 356). In SAP2000, the displacement controlled hinge is assigned directly at the ends of the member by auto hinge option which saves the computational effort. P-Delta effect, Rayleigh (Mass-Stiffness proportion) damping, and Hiber-Hughes-Taylor time integration method were considered in this direct integration type NLTHA analysis.

4. 2. Existing DI of Structure There are several methods available for estimating DI considering response parameters such as ductility, stiffness, yield displacement, peak roof displacement, joint rotation, no of inelastic loops, and IDR. In this study, Park-Ang method has been manoeuvred as it performed 142 monotonic and 261 cyclic test specimens experimentally considering both deformation and cyclic loading effect to estimate the damage in individual structural member, storey damage and global damage (Equations (1), (2) and (3)). But the main drawback of this method is that it takes huge time to estimate GDI of the structure and not suitable for large scale assessment. Different damage state is presented in supplementary Table 4 recommended by Park and Ang.

$$D=\left(\frac{\delta_M}{\delta_u}+\frac{\beta}{Q_y\delta_u}\int dE\right) \tag{1}$$

where D= 0 indicates no damage, D≥1 indicates total damage or collapse, δ_M = maximum deformation under earthquake, δ_u = ultimate deformation under monotonic loading, Q_y = calculated yield strength, dE = incremental absorbed hysteretic energy, β = non-negative parameters.

Storey DI and GDI is calculated by using Equations (2) and (3) respectively,

$$D_{storey}=\frac{\sum_{i=1}^{N} D_i E_i}{\sum_{i=1}^{N} E_i} \tag{2}$$

$$D_{global}=\frac{\sum_{storey,\, i=1}^{N} D_{storey,\,i} E_{storey,\,i}}{\sum_{storey,\, i=1}^{N} E_{storey,i}} \tag{3}$$

D_{storey} = DI of a storey i.e storey damage, D_i = DI of a member, E_i = Dissipated Hysteretic energy of a member, E_{storey}, i = Dissipated Hysteretic energy of the entire storey, D_{global} = DI of a structure i.e. global damage (GDI).

5. PROPOSED DAMAGE ESTIMATION PROCEDURE

Limited numbers of research have been carried out previously using multiple parameters for damage assessment. Damage assessment with multiple EDPs estimate reliable damage as each parameter contributes to individual damage characteristics. In this study, the most three influential parameters are joint rotation, IDR and peak roof displacement. They are combined in a mathematical expression to express the actual damage state of a structure. Most three influential parameters are selected among six EDPs inter-story drift (IDR), joint rotation, dissipated hysteretic energy, peak roof displacement, stiffness, and ductility from correlation matrix (supplementary Tables 5, 6 and 7) as their R^2 is maximum therefore could be considered as the most influential variables on DI. Multiple linear regression analysis has been performed in MATLAB2013a for combining these parameters in a suitable Equation (4). A new concept of DI has been proposed as the following form considering triple variables such as joint rotation, IDR and peak roof displacement are mentioned as:

$$\begin{aligned} &\textit{For rectangular shape}, GDI = 0.0964\times \mathrm{IDR}+12.53\times\theta-0.0129\times \mathrm{d}_{\max}+0.157 \\ &\textit{For U shape}, GDI = -0.0911\times \mathrm{IDR}+49.6423\times\theta-0.8371\times \mathrm{d}_{\max}+0.0898 \\ &\textit{For L shape}, GDI = 0.1369\times \mathrm{IDR}\text{-}20.3297\times\theta+2.7062\times \mathrm{d}_{\max}+0.0711 \end{aligned} \qquad (4)$$

where DI = Global Damage of the building; IDR = Maximum Inter-Storey drift ratio (%); θ = Maximum Joint rotation in a building (radian); d_{max} = Peak roof displacement (m)

The coefficients of EDPs were determined by multiple linear regression analysis with 126 data points of the top three influential parameters obtained from the considered simulated models. In Equation (4) maximum joint rotation, IDR and peak roof displacement is used to estimate global DI of the structure directly irrespective of shape and size of the structure. In this approach, the percentage of average error is quite low i.e. 8.7, 12.2 and 14.5% for rectangular, U shaped and L shaped building respectively. The proposed approach is depicted in a flow chart in Figure 3.

On the other hand, the ground storey DI is higher than global DI, therefore, ground storey DI should get prior importance than GDI. As ground storey is experiencing maximum damage, therefore the contribution of ground storey DI on global DI is maximum. Comparing GDI and ground storey DI, it is observed that 0.529 times ground storey DI represents (Equation (5)) equivalent global DI. This empirical expression is shown in Equation (5).

$$GDI = 0.529\times \textit{Ground storey damage index} \qquad (5)$$

6. RESULTS AND DISCUSSIONS

In a multi-story framed structure the number of member will be large. Estimation of GDI considering each member is a very tedious and time-consuming job. Therefore, authors have made an attempt to establish a relationship between most influential response parameters and Park-Ang GDI of structure. Comparison between proposed DI with Park-Ang global DI is plotted and it expresses the accuracy (R^2=0.88) of the proposed approach. The estimated slope of Equation (4) is 0.91, indicates a good agreement between these two methods.

Ground storey DI is higher than global DI therefore ground storey DI is more important than GDI. This approach significantly reduces computation time and would be suitable for both small and large scale damage assessment. Storey wise DI and global DI for both X and Y directions under seven SCGM are plotted in supplementary Figures 3 and 4, respectively. In supplementary Figure 4, the variation of GDI with earthquake (EQ) intensity along with PAR has been compared and presented for all cases. It has been observed that the highest DI found when PAR is 0.5, and the lowest DI found when PAR is 1.0 indicating square planner building shape suffers lesser damage. This is because of equal/balance redistribution of load/moment in the respective members or joints and perform well, hence recommending this shape as the best and safest configuration for any modern buildings. It has also been observed that the estimated values of storey DI (SDI) for a ground floor is maximum and for the top is minimum for all cases. Similar storey wise DI patterns were reported in literature [7, 17, 18]. Therefore, the contribution of the ground storey on GDI is maximum and local damage concentration occurs at the ground storey. From the present investigation, a useful correlation has been observed between GDI and ground storey SDI (Equation (5)). For example, ground storey DI is 0.575 and the estimated GDI is 0.301 so, GDI to ground storey DI ratio is 0.523. In this way, the multiplying factor (0.529 i.e. Average of all factors) is obtained after calculating all storey's SDI and GDI of

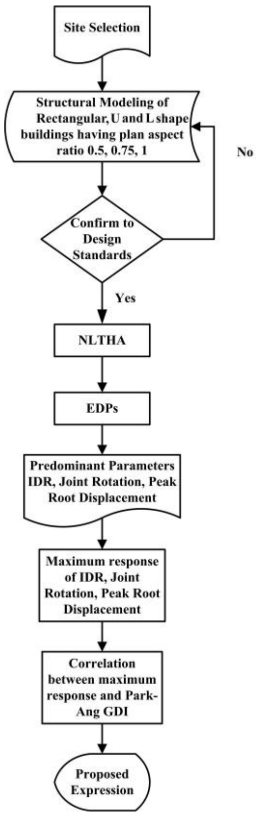
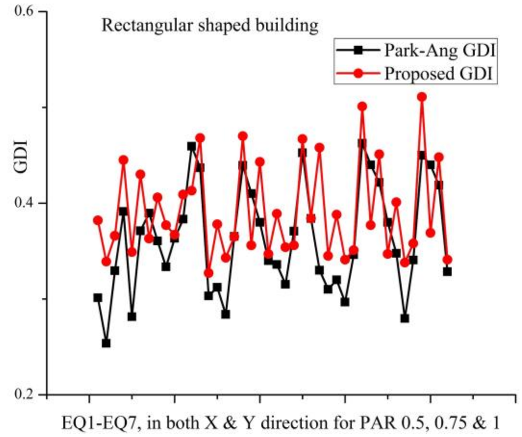
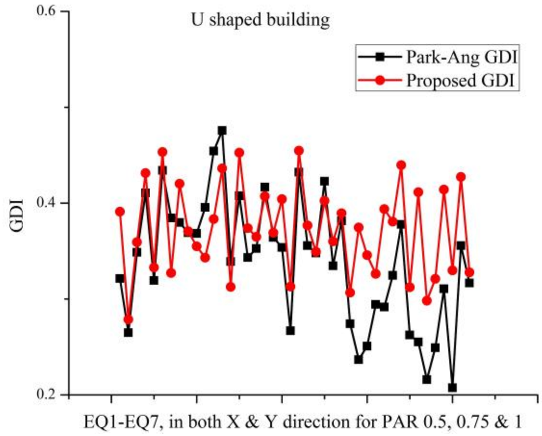


Figure 3. Seven real recorded ground motion

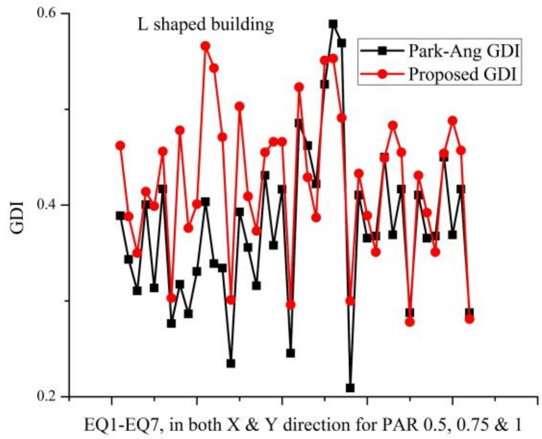
all the buildings. To validate the proposed method, the proposed GDI of another three typical samples of 8 storey buildings with different storey height (storey height = 3.5m) have been compared with Park-Ang GDI and plotted in Figure 4. Empirically calculated GDI (Equation (4)) and Park-Ang GDI is plotted to check the level of accuracy of the empirical formula where R^2 = 0.88 shown in Figure 5. It has been observed that in some storey, SDI is greater than GDI. For an example, a SDI is 1.5 whereas GDI is 0.6. That means the storey is completely damaged or irreparable whereas the GDI indicates a moderate level of damage. For this reason, storey DI is more important than GDI.



(a)



(b)



(c)

Figure 4. Shows the comparison of Proposed GDI [Equation (4)] with Park and Ang GDI (a) Rectangular Plan (Average error 8.7%) (b) U shape plan (Average error 12.2%) (c) L shape plan (Average error 14.5%)

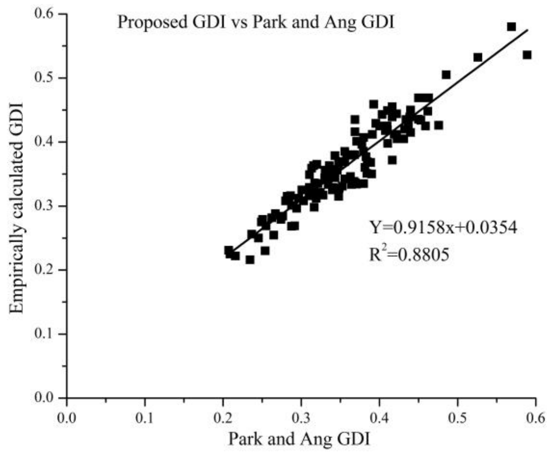


Figure 5. Actual GDI vs. Empirically calculated global damage index (from Equation (4))

7. CONCLUSION

In this study, the structural damage of RC buildings subjected to seismic load have been investigated. Figures 4 and 5 clearly explain that the proposed GDI model is efficient, reliable and easy for application for both regular and irregular buildings irrespective of its shape and size. Analysing the results, the following conclusions may be derived from the present study:

i) Although, the capacity of all storey is uniform (C/B ratio 1.4) nevertheless, ground storey experiences the highest damage that contributes maximum in GDI that implies ground storey is the most vulnerable storey in a building.

ii) The roof floor is experiencing the least damage as compared to the other floors for all cases. Moreover, the amount of hysteretic energy for the roof was minimum, so it can be concluded that the minor damage observed in this storey is mainly due to the drift effect.

iii) The proposed expression (Equations (4) and (5)) simplifies the method of Park-Ang DI that significantly reduces computation time and effort. Therefore, this method is suitable for rapid evaluation of large scale damage assessment of buildings efficiently.

iv) To estimate GDI, Equation (4) is the most useful and efficient and can be applied for any kind of building e.g. bare frame, frame shear wall building directly. As the ground storey is the most vulnerable region, therefore authors have emphasized to correlate ground storey DI with global DI. In this context, GDI can also be estimated empirically using Equation (5).

v) On the basis of correlation matrix among the six selected EDPs, it could be concluded that IDR, joint rotation, and peak roof displacement yields with the GDI and could be considered as the most influential/predominant EDPs. Therefore, this method must be adoptable to estimate global DI of structure.

vi) It has been observed that PAR 0.5 is experiencing the most damage (supplementary Figure 4) and PAR 1 is experiencing the least damage. It implies that due to torsional effect irregular buildings experience higher damage compared to regular shaped building. Therefore it is recommended to maintain the regular shape with PAR nearer to 1.

8. REFERENCES

1. Young-Ji, P., H-S, A., "Mechanistic Seismic Damage Model For Reinforced Concrete", ***Journal of Structural Engineering***, Vol. 111, No. 4, (1985), 722-739.
2. Young-Ji, P., Alfredo H.-S, A., Yi Kwei, W., "Seismic Damage Analysis of Reinforced concrete Buildings", ***Journal of Structural Engineering***, Vol. 111, No. 4, (1985), 740-757.
3. Wong, K. K. F. and Wang, Y., "Probabilistic Structural Damage Assessment And Control Based On Energy Approach", The Structural Design of Tall and Special Buildings, Wiley Online Library, Vol. 10, (2001), 283-308.
4. Carrillo, J. "Damage index based on stiffness degradation of low-rise RC walls", ***Earthquake Engineering & Structural Dynamics,*** Vol. 44, (2015), 831–848.
5. Siqi, Tianlai, Y., and Junfeng, J., "Investigation and Analysis of Empirical Field Seismic Damage to Bottom Frame Seismic Wall Masonry Structure", ***International Journal of Engineering, Transactions B: Applications,*** Vol. 32, No. 8,(2019), 1082-1089.
6. Jeong, S-H, Elnashai, AS. "New Three Dimensional Damage Index for RC Buildings with Planar Irregularities", ***Journal of Structural Engineering***, Vol. 132, No. 9, (2006), 1482-1490.
7. Alhaddad, M.S., Wazira, K.M., Al-Salloum, Y.A., Abbas, H., "Ductility damage indices based on seismic performance of RC frames", ***Soil Dynamics and Earthquake Engineering***, Vol. 77, (2015), 226–237.
8. Nader, C. and Farid, T. A "Damage Index for Structural Health Monitoring Based on the Empirical Mode Decomposition", ***Journal of Mechanics of Materials and Structures,*** Vol. 2, No. 1, (2007), 43-61.
9. Ghobarah, A., Abou-Elfath, H., Biddah, A., "Response Based Damage Assessment of Structures", ***Earthquake Engineering And Structural Dynamics***, Vol. 28, (1999), 79-104.
10. Hait, P., Sil, A., Choudhury, S., "Quantification of damage to RC structures: A comprehensive review", ***Disaster Advances,*** Vol. 11, No. 12, (2018), 41–59.
11. Hait, P., Sil, A., Choudhury, S., "Overview on damage assessment of structures", ***Current Science,*** Vol. 117, No. 1, (2019).
12. Sil, A., Sherpa D. Z., Hait P., "Assessment on combined effects of multiple engineering demand parameters (MEDP) contributing on the shape of fragility curve", ***Journal of Building Pathology and Rehabilitation***, Vol. 4, No. 5, (2019), 3-17.
13. Plain and Reinforced Concrete. Plain and Reinforced Concrete – Code of practice, IS 456 2000.
14. Criteria for Earthquake Resistant Design of Structures IS:1893 2016, December 2016.
15. Ductile design and detailing of reinforced concrete structures subjected to seismic forces- code of practice IS 13920 2016, Bureau Of Indian Standards.
16. Prestandard and commentary for the seismic rehabilitation of buildings, FEMA 356 ASCE, 2000.
17. Young J. P., Reinhorn, A. M., and Kunnath, S. K., "Seismic damage analysis of reinforced concrete buildings", Proceedings of Ninth World Conference On Earthquake Engineering, Vol. 7, (1988).
18. Young, J. P., Reinhorn, A. M. and Kunnath, S. K., IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame-Share Wall Structures, Dept. of Civil Engineering, State University of New York at Buffalo, (1987).

Damage Assessment of Reinforced Concrete Buildings Considering Irregularities

RESEARCH NOTE

P. Hait, A. Sil, S. Choudhury

Civil Engineering Department, National Institute of Technology Silchar, Assam, India

PAPER INFO

Paper history:
Received 7 June 2019
Received in revised form 28 August 2019
Accepted 12 September 2019

Keywords:
Damage Assessment
Engineering Demand Parameter
Local and Global Damage Index
Non-linear Time History Analysis
Reinforced Concrete Framed Building

چکیده

خسارت ساختاری را می توان در طراحی لرزه ای مبتنی بر عملکرد (*PBSD*) با توجه به نیاز تحت یک سطح خاص خطر کنترل کرد. در حین حرکت شدید زمین (*GM*) ، چنین ساختمانهایی بسته به سطح لرزش *GM* از خسارت های عمده ای برخوردار هستند. روشهای ارزیابی آسیب های موجود روشی پیچیده ، خسته کننده و وقت گیر است. در مطالعه حاضر ، یک مدل تجربی ساده ارائه شده است که *GDI* را در یک مرحله با استفاده از پارامترهای تقاضای مهندسی (*EDP*) یعنی چرخش مشترک ، رانش بین طبقه (*IDR*)، جابجایی سقف اوج محاسبه می کند. مشخص شده است که روش پیشنهادی نتایج *GDI* را به مدل *Park-Ang* نزدیک می کند. مشاهده شده است که طبقه همکف برای همه موارد بیشترین خسارت را متحمل می شود. علاوه بر این ، بین داستان زمینی *DI* و جهانی *DI* رابطه ای برقرار شده است. مدل پیشنهادی به طور مؤثر از *DI* قابل اطمینان ترمیم می کند و می تواند به عنوان ابزاری قدرتمند برای برآورد خسارت لرزه ای در ساختمان ها ، به ویژه برای سازه های عظیم مورد استفاده قرار گیرد.

doi*: 10.5829/ije.2019.32.10a.08*