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Original Article

Development of Absorbed Energy and Stiffness-Based Damage Index for Vertical Irregular Buildings

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Abstract - *In the present study, the seismic damage of a building is estimated as damage indices based on absorbed energy and degraded stiffness by performing pushover analysis. A new stiffness-based damage index is proposed, considering the cumulative effects of increasing each lateral load or displacement for each step of nonlinear static analysis. A non-cumulative absorbed energy-based damage index is presented using the pushover curve's first maximum hysteretic cycle. The proposed methods are applied on 4, 6 and 9-storey regular and vertical irregular setback types of 3D buildings. Three regular and irregular buildings of varying heights, setback directions and monotonic loads are selected to estimate the capability of the proposed damage indices. Further, the proposed damage indices are calibrated with existing deformation and strength-based damage indices. Both damage indices can calculate damage index at any point of the pushover curve; however, the damage indices are computed on different performance levels during this study. The damage index studies demonstrated that two methods for evaluating damage to irregular buildings are simple and accurate; they could also help designers estimate the global damage index as a performance criterion in a short time using pushover analysis results.*

Keywords - *Energy-based damage index, Performance-based seismic design, Pushover analysis, Stiffness-based damage index, Vertical irregular buildings.*

1. Introduction

Recent earthquakes in many parts of the world have highlighted the need for a major change in the current seismic design method. Force-based seismic design IS code is now in use, meaning that forces and displacements within elastic limits are computed and combined to design structural elements [1]. Earthquake proof design is not possible, but every structure must be designed to withstand earthquakes. As a result, engineers can allow for some damage to structures in earthquake disasters. Irregular plans and elevation configurations have been found to be a primary reason for structural damage during previous earthquakes [2]. Estimating the amount of seismic damage a structure will likely sustain over its design life. Some researchers have introduced deterministic and probabilistic methods [3]. A distinction between deterministic and probabilistic indices may be formed depending on the mathematical approach used to compute the damage index (DI). Out of these two approaches, the deterministic approach is primarily chosen by researchers because of its simplicity and ability to be utilised immediately in a practical context. Further, most importantly, the computing time for determining them is much lower than that of probabilistic indices [4]. Many researchers have proposed deterministic approaches [5, 6, 7, 8, 9, and 10] using various Engineering demand parameters (EDP). The structural damage value has been calculated in the relevant literature using two main techniques. The first method is based on a balance between a structure's demand and capacity, and the second method is based on degrading the EDPs such as stiffness, strength, ductility and using other EDPs. Researchers have proposed several damage index estimation techniques for different structures in the past based on single and multiple EDPs. Zameeruddin et al. (2020) [11] proposed DI calculation techniques based on energy, stiffness, strength, and ductility parameters, and Vimala A. et al. (2014) [9] had given empirical formula to compute DI using dissipated energy; both studies were done on 2D regular frames with using nonlinear static analysis on various performance levels. Habibi A. et al. (2012, 2013 & 2016) [2,12-13] worked on absorbed energy, ductility, stiffness, and drift-based computation on 2D setback frames by using nonlinear dynamic analysis, Ghobarah A. et al. (1999) [8] studied for computation of stiffness based DI, but these researches ignored the torsional effects. S. Diaz et al. (2017) [14] studied damage estimation in terms of stiffness, ductility, and dissipated energy, although the analysis did not consider torsion and bidirectional moment effects. Pritam H. et al. (2020) [7] studied damage index estimation using inter-storey drift, joint rotation and peak displacement on regular buildings and have been suggested to work out ductility, dissipated energy, and stiffness parameters. P. Hait et al. (2019) [15] used various EDPs such as inter-storey drift, joint rotation and maximum displacement to assess the damage on different plan irregular buildings. However, the authors did not account for torsional effects in their investigation. Cinitha A. et al. (2015) [10] proposed a time-period-based softening damage index and a fully elastic-plastic damage index based on spectrum displacement and acceleration. M. Zameeruddin et al. (2017) [16] developed a new empirical technique for determining stiffness-based damage indices that considered the cumulative impact of deteriorating stiffness and disregarded torsion effects while using nonlinear static analysis in regular frames. S. Jeong et al. (2006) [17] had considered torsional and geometrical irregularities; however, the application in high-rise buildings remained unclear. Many studies have been conducted about the suitability of various seismic code provisions for these buildings. The present seismic codes have suggested certain special needs to offer the expected seismic performance of these structures [13].

According to existing literature studies, several DI estimate techniques have become available using nonlinear static and dynamic analysis; however, they are either difficult or inefficient against irregular 3D buildings. Several studies have identified that structural damage is estimated using one or two parameters: stiffness, dissipated energy, ductility, rotation, inter-storey drift (IDR), and maximum lateral deformation. Still, it would be better to estimate damage using multiple response parameters that describe the actual damage scenario of a structure under seismic conditions [7]. Further, nonlinear dynamic analysis requires a complex mathematical long time for calculations and different ground data. So, the alternative method of nonlinear static analysis (pushover analysis) has made attention in the design industry as it involves less time-consuming and easy to use compared to nonlinear time history analysis [16]. Vertical discontinuities in the distribution of strength, stiffness, and mass are the features of vertical irregularities. Most studies have focused on the elastic response, and very few studies have been conducted to investigate the consequences of discontinuities in each of these parameters separately [27].

In this study, the limitations of earlier research are critically studied, and damage indices are proposed that enable pushover studies to quantify the effects of stiffness degradation and energy dissipation after each incremental displacement. This study's main objective is to estimate the damage in terms of DI on low to medium-rise RC regular and setback types of vertical irregular buildings. The relationship between absorbed energy and degrading stiffness with lateral drift is developed to make the DI estimate process more accessible and simple. These suggested approaches may be used to quickly calculate the global damage index for irregular 3D small to large-scale buildings, taking into account the most significant EDPs, such as absorbed energy and degrading stiffness, and have attempted to simplify the damage estimation technique.

2. Seismic damage index

The main cause of damage in irregular RC structures is the failure of the element, which occurs due to substantial deformation and concrete becoming in a nonlinear state [18]. Due to unpredictable building reactions, calculating the damage index of irregular buildings is important. The important criteria are strength, stiffness, flexibility, lateral displacement (drift), torsion, and other EDPs used to characterise the failure process [5]. In the current work, modified stiffness-based and energy-based damage indexes are developed and used for a wide range of irregular 3D buildings with significant torsion caused by the unexpected response due to vertical irregularities. Most damage indices primarily examine flexural yielding for beams and columns. The suggested approach applies to any type of plastic hinges subjected to nonlinear analysis. The new damage indices (DIs) evaluation has several advantages and limitations, which are listed below.

Advantages

1) The DI is appropriate for estimating structural stiffness variations and absorbed energy associated with the first hysteretic cycle on different performance levels. 2) Instead of assuming the maximum displacement or deformation of the structure near collapse on the pushover curve, damage may be assessed at any loading level on the curve. 3) Damage caused by processes other than flexural yielding can be modelled using the suggested indices. In this instance, all probable failure modes can be included in the models. 4) The stiffness is calculated after applying the lateral load of each incremental step of pushover analysis and based on that, DI is calculated considering the cumulative effect of stiffness degradation. Instead, stiffness computation after eliminating the inertia and damping force effects and bringing the frame to a static condition. 5) In the pushover analysis, various degrading stiffness may be computed depending on the load direction at different performance levels. 6) It is easy to use, takes a few calculations, and is a good alternative to nonlinear time history analysis. It eliminates nonlinear time history analysis, which is difficult, time-consuming, and necessitates a lot of ground motion data.

Limitations

1) The pushover analysis technique's limitations impact the applicability and reliability of the suggested damage estimation. 2) It necessitates precise nonlinear modelling; else, nonlinear outcomes would be inaccurate.
The proposed DIs are briefly explained below.

2.1. Energy based damage index (EBDI)

Pushover curves are formed in both directions by applying monotonic load in various patterns such as (uniform) acceleration, IS 1893-2016 (inverted triangle), and mode type (parabolic curve), as shown in figure 6. The area under the curve represents the amount of energy absorbed by the building. This area computation technique aims to integrate the cumulative cyclic loading effects, avoiding the need for nonlinear dynamic analysis because it follows the collapse process from the pushover curve. The inelastic energy in equation (1) represents the various energies expended by permanent plastic rotations in beams and columns, indicating the degree of damage while executing dynamic loadings. The first hysteretic cycle was used as a pushover curve and by estimating the area under the curve at different performance levels. The optimal amount of different energies was absorbed through the lateral load. Damage is calculated as the ratio of the difference between absorbed energy at the intended performance level and energy absorbed at the elastic performance level to the difference between absorbed energy at the ultimate displacement point and energy absorbed at the elastic performance level as indicated in equation (2).

E_i (input energy) = $E_e + E_d$ (1)

Where, E_e (elastic strain energy) = E_k (kinetic energy) + E_s (strain energy), & E_d (dissipated energy) = E_h (hysteretic energy) + E_ζ (viscous damping energy)

The absorbed energy at the operational level (E_{op}) is depicted in Figure 1a, which is defined as the area under the pushover curve up to the curve's first yielding point. The energy absorbed by the structure up to any specified performance point, when the damage is estimated as indicated in figure1b, is termed energy at the targeted performance point.

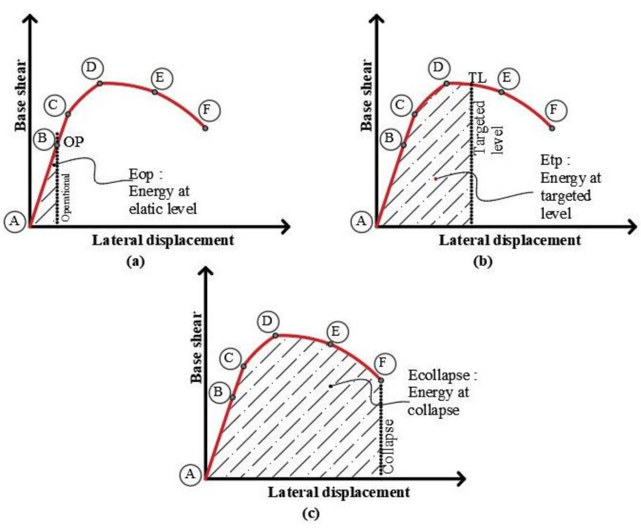

Fig. 1 (a), (b) & (c) various absorbed energy on critical points of the curve

The structure's full nonlinear energy capacity is defined as the area covered up to the final lateral displacement point, as shown in figure 1c ($E_{collpase}$). (Area beneath the curve from the point of collapse to the point of collapse.)

The polynomial equation of the fitting curve is shown in figure 2. At a given point on the pushover curve, equation (2) is utilized to calculate an energy-based damage index, and equation (3) is used to calculate absorbed energy.

$$\text{Damage index (Di }_{\text{Energy}}) = \frac{E_{t.p} - E_{op.}}{E_{co.} - E_{op.}} \quad (2)$$

$$\text{Energy @ t.p} = \int_0^{S_{d(t.p)}} (ax^n + bx^n + C)dx \quad (3)$$

Where E $_{(t.p)}$ targeted point = Absorbed energy at targeted performance level

$E_{op.}$ = Absorbed energy at the operational level, & $E_{co.}$ = Absorbed energy at collapse level

2.2. Stiffness based damage index (SBDI)

In pushover analysis, the structure's stiffness reduces with each incremental step and depends on various parameters. Powell & Allahabadi (1988) [5] were the first to investigate the stiffness based damage index and to conduct a nonlinear time history analysis. In 1999, Ghobarah et al. [19] developed a novel empirical technique based on pushover and nonlinear time history analysis. But, due to certain limitations, M. Zameeruddin et al.(2017) [11] updated the idea and addressed the cumulative impacts of stiffness degradation parameters using nonlinear static analysis. That empirical formula is mostly utilized for regular frames. This research proposes a suggested technique for the deterioration of stiffness with increasing lateral load. The cumulative impacts of each incremental step were examined using the new methodology. Two modifications must be considered when considering progressive stiffness degradation: the first at the plastic hinge positions and types and the second at the gradual member stiffness deterioration between two plastic hinges.

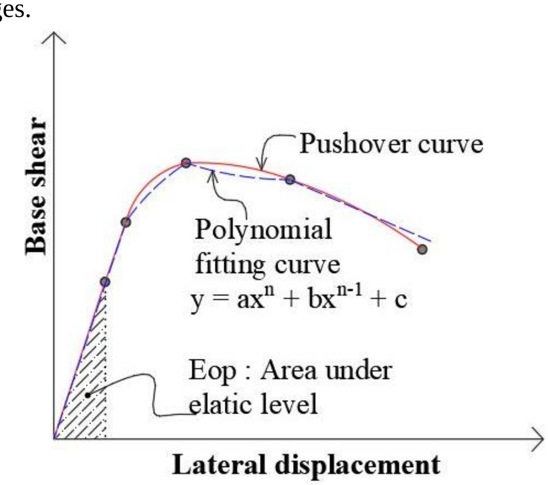

Fig. 2 Typical performance levels on pushover curve

A cross-section stiffness (two-surface) degradation function is utilized to highlight the gradual yielding impact in the development of plastic hinges.

The initial slope measured at the different key locations of the pushover curve is used to calculate the stiffness based damage index. The stiffness of a structure is directly and inversely related to the imposed monotonic lateral load and displacement. The initial slope is used to determine stiffness at each performance level. To compute a stiffness-based damage index at a given displacement on the pushover curve, equation (4) is proposed. As illustrated in figure 3, nonlinear components depending on stiffness are used in the computation.

$$DI_{k@t.p} = 1 - \frac{\sum V}{\sum K * d} \tag{4}$$

Where, DI_k, targeted point = stiffness based damage index at targeted performance level

$\sum V = V_1 + V_2 + V_3 + \text{---} + V_n$ (Summation of base shear up to targeted performance level)

$\sum K = K_1 + K_2 + K_3 + \text{---} + K_n$ (Summation of stiffness up to targeted performance level)

Where 1, 2, 3 -----n are the incremental lateral steps
D = Corresponding lateral displacement at targeted performance level

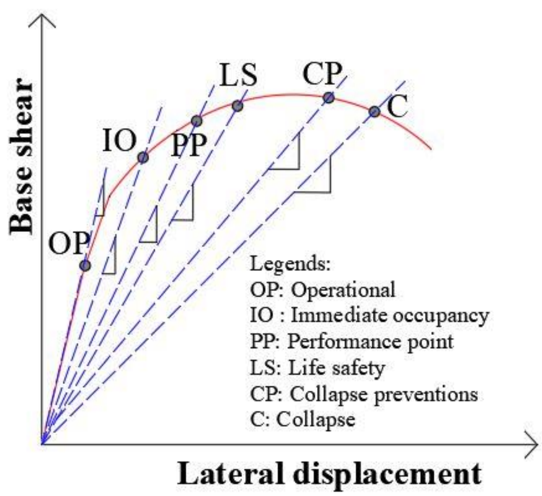

Fig. 3 Stiffness based nonlinear parameters

3. Performance based seismic design

The lateral deformation and damage tolerance of buildings are estimated using a performance based seismic design technique for multiple performance levels and at a performance point [10-20]. Different performance levels, such as operational (OP), immediate occupancy (IO), life safety (LS), collapse prevention (CP), and collapse (C) [22-23], indicate limited seismic damage states that may or may not be fulfilled under earthquake loads. Figure 4 depicts a conceptual flowchart for evaluating the seismic performance of RC buildings in terms of damage index. The most important element of defining performance targets in PBSD is selecting design criteria. Every performance target is explicitly specified in the form of statements in FEMA 273/356 [22], SEAOC Vision 2000 [24], and ATC 40/58 [23], and the indication is based on an acceptable risk of damage to structural elements at predefined plastic hinge positions at particular levels of seismic hazard [19]. The various performance levels developed in PBSD are based on the permanent and transient drift, as illustrated in table 1. The inelastic response is assessed using nonlinear static and dynamic analysis to determine the structure's performance level.

It should be noted that pushover analysis is an approximate performance-based seismic design technique with certain limitations in terms of dynamic features such as increased mode involvement, hysteresis loops, and so on [1]. The main aims of the performance-based seismic design method are to predict and mitigate the damage to a structure that has been exposed to an earthquake. This design technique involves a range of procedures for designing a structure in a controlled manner such that its response under earthquake loading is ensured at predetermined performance levels [13].

The pushover curve is transformed into an acceleration displacement response spectrum (ADRS) in these instances, indicating the structure's seismic capacity and performance point. Figure 5 shows an idealized depiction [23] of the performance point, which is the junction point of the pushover curve and the response spectrum. The pushover curve is recognised without considering the torsion irregularities caused by structure, and suitable findings are given for regular structure [30].

Table 1. Different performance levels in available standard

FEMA 273/356 [22]	ATC 40/58 [23]	SEAOC Vision 2000 [24]
Performance level	**Projected damage**	**Expected performance**
Immediate occupancy (IO)	Negligible	Fully operational
Damage control range (DCR)	Light	Operational
Life safety (LS)	Moderate	Life safe
Limited safety range (LSR)	Severe	Near collapse
Collapse prevention (CP)	Complete	Total collapse

FEMA 273/356 [22], ATC 40/58 [23], and SEOAC vision [24] define the various performance levels, which are shown in figure 3. Different drift limits of different performance levels are depicted in table 2. The various performance levels in ascending order regarding lateral load or displacement are stated here.

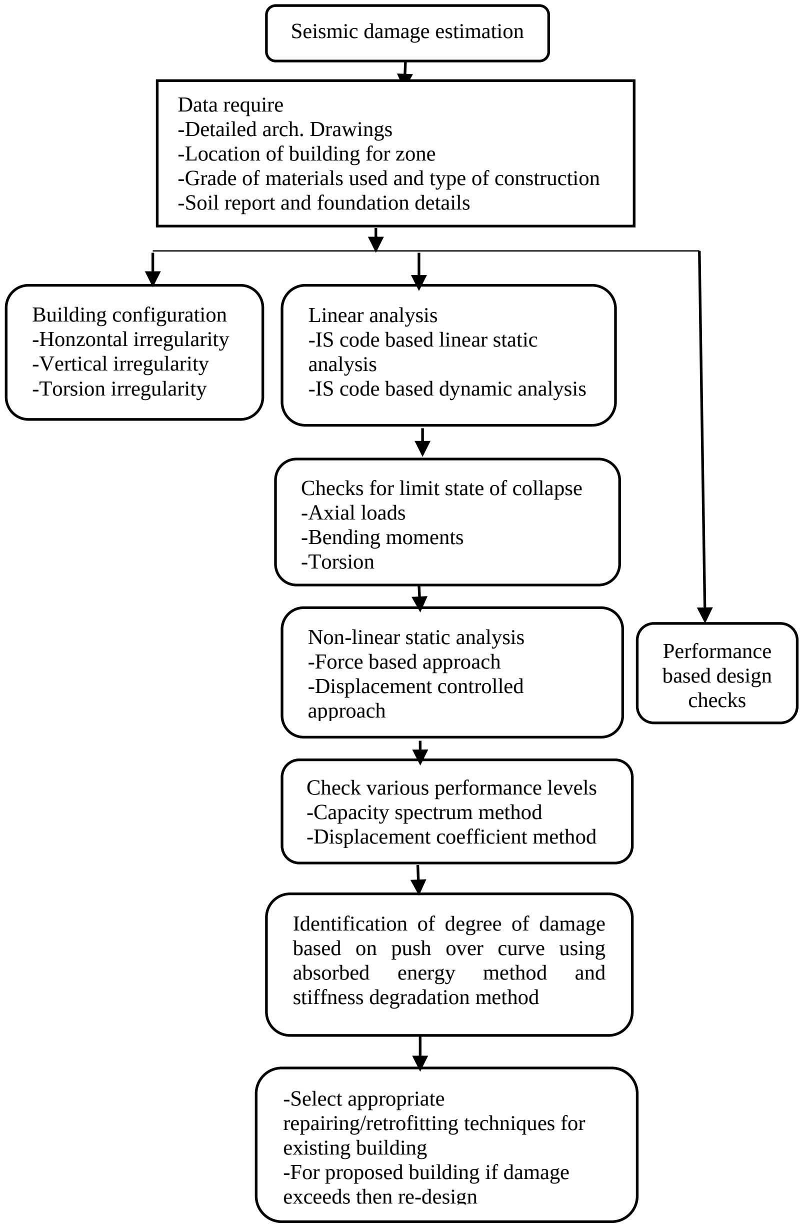

Fig. 4 Flowchart for seismic damage evaluation in terms of damage index

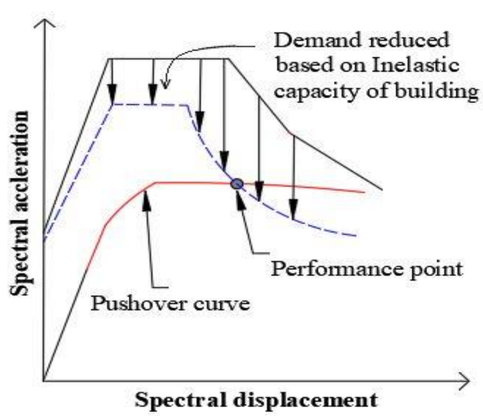

Fig. 5 Idealized representation of performance point of ATC -40 [23]

1) Operational level (OP): This performance level is carried out up to the structure's elastic limit; no damage occurs at this level. Because it is solely in the elastic limit, the results are nearly identical to those of the linear static or dynamic analysis. 2) Immediate occupancy (IO): This performance level extends above the structure's elastic limit, resulting in a nonlinear response, although it is still deemed safe after an earthquake. Structures can be used right away after an earthquake. 2a) Damage control range (DCR): This performance level falls between the range of IO and LS. 3) Life Safety (LS): This performance level is carried out at the strain hardening stage and within the repairable damage range. There is no damage allowed to people's lives. Most structures are built to a degree of life safety.3a) Limited safety range (LSR): This performance level falls between the range of LS and CP. At this level, some repairable damage can occur with complete life safety. 4) Collapse prevention (CP): This performance level is well-suited to gravity loads following an earthquake when the structure partially collapses in the elements but does not entirely collapse (Serviceable even after some damage to elements). 5) Collapse (C): This performance level is no longer usable and cannot provide life safety against gravity loads after an earthquake.

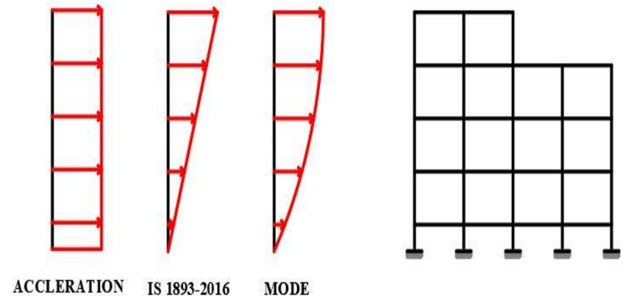

Fig. 6 Monotonic load patterns

Table 2. Drift limits at different performance levels [22-23]

Performance level	Description	Drift limits
Operational (OP)	Does not undergo any damage	< 0.7 %
Immediate occupancy (IO)	Elements are partially damaged	1 %
Life safety (LS)	Remarkably damage to structural and nonstructural elements	2 %
Collapse prevention (CP)	Structural elements are about to collapse	4 %
Operational (OP)	Does not undergo any damage	< 0.7 %

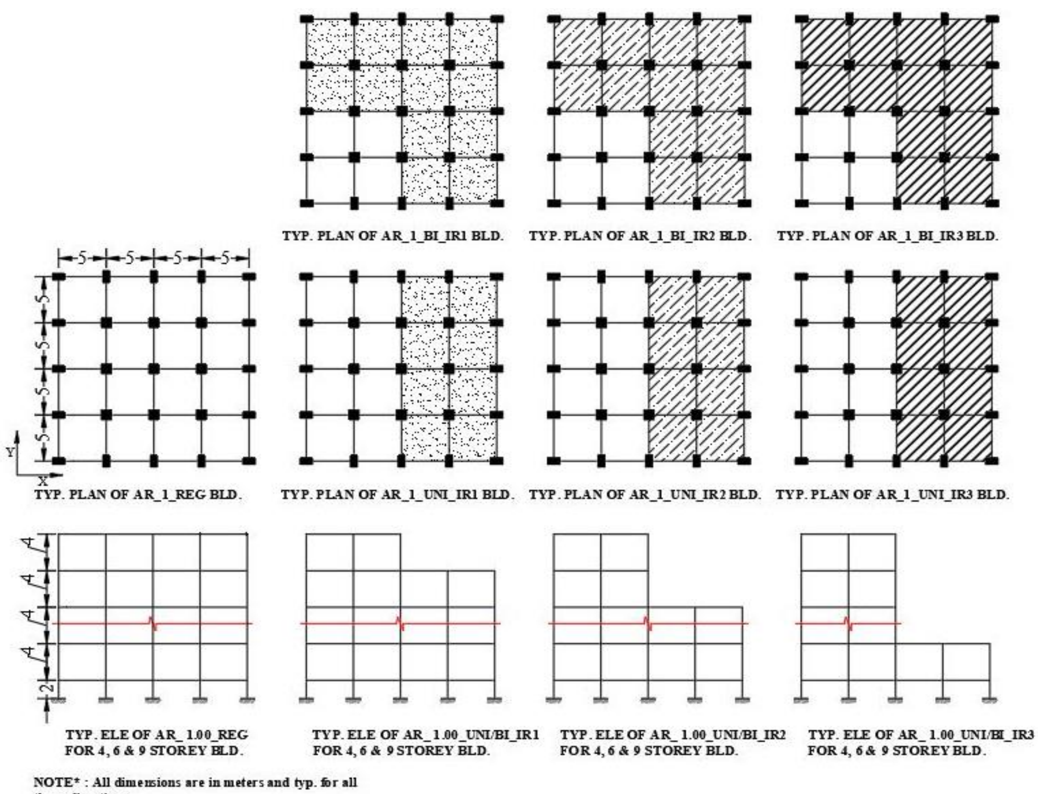

Fig. 7 Typical plans and elevations of 4, 6, and 9-storey buildings

4. Description of building example

The suggested DIs were applied to 4, 6, and 9-storey regular and vertical irregular RC buildings with setbacks in unidirectional and bidirectional types, as shown in figure 7. Three distinct three-dimensional buildings are represented in short, medium, and long periods. The foundation and remaining floor heights are 2 m and 4 m, respectively. Buildings are designated, e.g. S4_UNI_IR1_X_ means 4 storeys with unidirectional setback type considering one storey (setback) irregular, and X indicates horizontal direction. Parametric studies were conducted to compute DIs considering three distinct monotonic loadings, two directions of setback and the three different storey irregularities. Rectangular (Exterior) columns are assumed to be 300 x 600 mm for 4 and 6-storey buildings and 300 x 750 mm for 9-storey buildings. For all buildings, square (interior) columns of 600 x 600 mm are assumed, and beams of 230 x 450 mm are taken for all floors. Buildings are designed using steel with a yield strength of 415 MPa for both main bars and lateral ties and concrete with a compressive strength of 25 MPa. A dead load of slab and floor finish are 3.75 kN/m^2 and 1.00 kN/m^2, respectively. Brick masonry wall thicknesses 230 mm and 115 mm are used on the exterior and internal beams, respectively. The live load of 2 kN/m^2 is applied to all slabs. Buildings are designed according to the IS 456-2000 [26] and IS 1893-2016 [25] codes, which include linear static and dynamic analysis. According to IS 1893-2016 [25], the seismic load is computed, and linear analysis is performed using zone factor 0.16, importance factor 1, and response reduction factor 5, with medium soil strata. IS 1893-2016 [25] proposes a reduced moment of inertia for structural elements such as beams and columns. As a result, the current research incorporates the strong column and weak beam concepts.

4.1. Nonlinear Modelling

The inelastic modelling of reinforced concrete members is critical to the effectiveness of nonlinear static procedures. The plastic hinges are used to introduce the inelastic properties of the reinforced concrete members. Plastic hinges can be deformation-controlled (ductile action) or force-controlled (brittle action), according to performance based seismic engineering (PBSE). In PBSE standards, plastic rotation limitations for reinforced concrete beams and columns are defined. In the current study, default deformation-controlled (ductile action) types of plastic hinge properties are assigned at 5 % apart from beam-column joints. The maximum displacement for each RC building was defined at 4 % of the building's height (ATC 40, 1996). Each Plastic hinge detail is given in the ideal force–deformation curve indicated in figure 8. When subjected to lateral loading, the most critical member represents the building's worst-case scenario. Acceleration, IS 1893, and mode types of loading patterns are applied to calculate the lateral seismic force distribution for the pushover study. The simplified load-deformation relationship presented in figure 8 represents a linear reaction from A to yield point B, followed by a linear response from B to C at reduced stiffness. Without any precise experiment value, the slope from point B to C can be assumed as 0–10 percent of the starting slope, ignoring the effects of vertical loads acting through lateral displacements. The ordinate of point C represents the member's maximum strength, whereas the D coordinate shows the deflection at which substantial strength reduction occurs. Line DE shows the structure's remaining strength.

Table 3. Pushover result for S9_BI_IR1_DF_ Acceleration- X dir._ case

Step no.	Disp. (mm)	Base Shear (kN)	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	Beyond E
0	0	0	1162	0	0	0	0	0	0	0
1	15.2	163.66	1162	0	0	0	0	0	0	0
6	106.4	1127.78	1076	86	0	0	0	0	0	0
19	288.8	1735.72	883	245	34	0	0	0	0	0
22	334.4	1822.94	851	221	89	0	1	0	0	0
44	668.8	2141.52	772	141	231	0	6	10	2	0

Table 4. Energy based damage index calculation for S9_BI_IR1_ DF_ Acceleration load- X dir._ case

Step no.	Disp. (mm)	Base Shear (kN)	Per. level	Region	Drift (%)	The area under the curve (kN-m)	Energy based damage index (%)	Remarks
0	0	0	-	-	0.000	-	-	Total 1162 hinges
1	15.2	163.66	OP	A-B	0.040		0.00	The first step of the Elastic range
5	76.0	818.38			0.200	-1.197	0.00	Last step of the Elastic range
6	91.2	982.05	IO	B-IO	0.240	-1.427	6.62	Hinge formation B-IO
7	106.4	1127.78	P.P	IO-LS	0.280	-1.654	13.15	P.P @ IO-LS
19	288.8	1735.72	LS	IO-LS	0.760	-4.124	84.29	Hinge @ IO-LS
21	319.2	1794.52	CP	LS-CP	0.840	-4.490	94.85	Hinge @ LS-CP
22	334.4	1822.94	C	CP-C-D-E	0.880	-4.467	100	Hinge @ CP-C-D-E

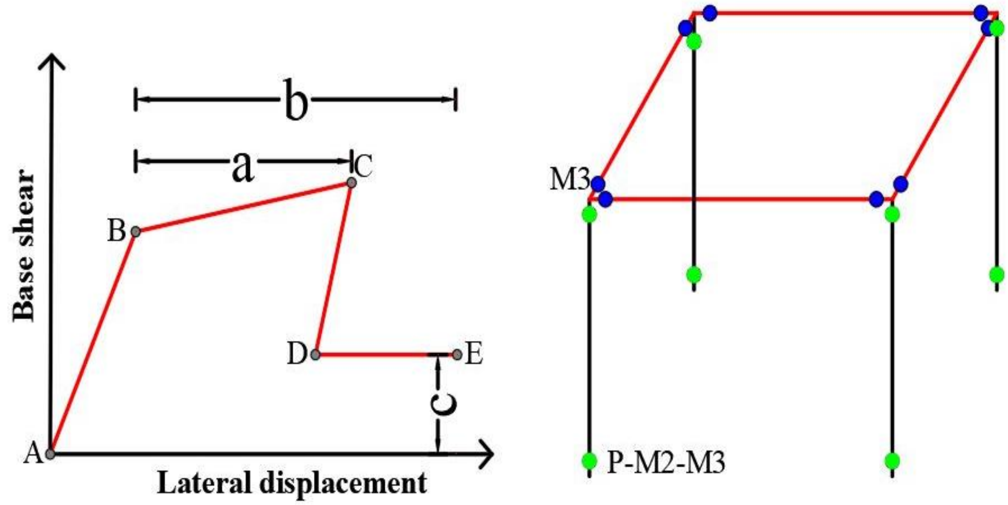

Fig. 8 Standard force-deformation curve and hinges details

Table 5. Stiffness based damage index calculation for S9_BI_IR1_ DF_ Acceleration load- X dir._ case

Step no.	Drift (%)	Stiffness (kN/m)	Cumulative base shear, $\sum K_o \times d_c$ (kN)	Sum. of base shear, $\sum V$ (kN)	Ratio of col.5/ col.4 (%)	Stiffness based damage index (%)	Remarks
1	0.040	10768.09	163.675	163.375	100.00	0.00	The first step of the Elastic range
6	0.240	10768.09	5892.300	3437.175	58.33	41.67	Hinge formation B-IO
7	0.280	10599.43	8002.129	4564.954	56.05	43.95	P.P @ IO-LS
19	0.760	6010.11	48442.298	22758.266	46.98	53.02	Hinge @ IO-LS
21	0.840	5621.93	57189.539	26318.055	46.02	53.98	Hinge @ LS-CP
22	0.880	5451.36	61735.785	28140.989	45.58	54.42	Hinge @ D-E

Table 6. Damage indices at performance levels on the curve of S9_BI_IR1_DF_ACCL._X

Performance level	S_d (mm)	Drift (%)	Di_E (%)	Di_K (%)	$Di_{P\&A}$ (%)	$Di_{Z\&K}$ (%)
OP	76.00	0.200	0.00	0.00	0.00	0.00
IO	91.20	0.240	6.62	41.67	5.88	49.32
P.P	106.4	0.280	13.15	43.95	11.76	58.10
LS	288.8	0.760	84.29	53.02	82.35	94.74
CP	319.2	0.840	94.85	53.98	94.12	98.29
C	334.4	0.880	100	54.42	100	100

Di_E = Energy based damage index, Di_k = Stiffness based damage index,
$Di_{P\&A}$ = Powell & Allahabadi's *deformation based damage index* (1988) [5]
$Di_{Z\&K}$ = Zameeruddin & K. Sanghle's *strength based damage index* (2017) [16]

Table 7. Various damage indices at performance point for 9- storey building

Sr. No.	Storey_ Reg./IR_DF_ Dir. [n]	Lateral loading type	S_d (mm)	Drift (%)	Di_E (%) Proposed	Di_K (%) Proposed	Di_D (%) P&A (1988) Existing	Di_V (%) Z&K (2017) Existing
1	S9_Reg_DF_X	Accl.	121.60	0.320	9.90	44.05	7.69	52.69
2		IS 1893	136.80	0.360	7.64	44.81	6.98	61.35
3		Mode-2	136.80	0.360	9.81	45.02	7.32	58.61
4	S9_Reg_DF_X	Accl.	121.60	0.320	10.38	44.13	8.11	54.57
5		IS 1893	136.80	0.360	8.48	45.04	7.32	63.45
6		Mode-1	136.80	0.360	8.63	45.00	7.89	60.21
7	S9_UNI_	Accl.	121.60	0.320	0.00	43.75	0.00	23.72

8	IR1_DF_X	IS 1893	152.00	0.400	0.00	45.00	0.00	30.27
9		Mode-2	136.80	0.360	0.00	44.44	0.00	25.70
10	S9_UNI_ IR1_DF_Y	Accl.	136.80	0.360	0.00	44.44	0.00	25.99
11		IS 1893	167.20	0.440	0.00	45.45	0.00	29.36
12		Mode-1	167.20	0.440	0.00	45.45	0.00	26.11
13	S9_UNI_ IR2_DF_X	Accl.	106.40	0.280	7.24	42.95	4.88	49.12
14		IS 1893	136.80	0.360	7.18	44.75	6.67	64.43
15		Mode-2	136.80	0.360	0.00	44.44	0.00	26.71
16	S9_UNI_ IR2_DF_Y	Accl.	121.60	0.320	6.04	43.95	5.41	52.14
17		IS 1893	152.00	0.400	7.26	45.37	6.82	62.83
18		Mode-1	167.20	0.440	0.00	45.45	0.00	26.44
19	S9_UNI_ IR3_DF_X	Accl.	106.40	0.280	5.80	42.95	4.65	49.26
20		IS 1893	136.80	0.360	4.65	44.63	4.35	64.89
21		Mode-2	121.60	0.320	5.04	43.89	4.35	57.03
22	S9_UNI_ IR3_DF_Y	Accl.	121.60	0.320	5.87	43.89	5.41	50.99
23		IS 1893	152.00	0.400	7.06	45.24	6.67	61.25
24		Mode-1	152.00	0.400	8.20	45.23	7.69	49.77
25	S9_BI_ IR1_DF_X	Accl.	106.40	0.280	13.15	42.95	11.76	58.10
26		IS 1893	136.80	0.360	8.28	44.99	6.23	61.90
27		Mode-2	136.80	0.360	14.57	45.31	10.26	59.59
28	S9_BI_ IR1_DF_Y	Accl.	121.60	0.320	11.77	44.13	9.68	56.63
29		IS 1893	136.80	0.360	7.65	44.87	6.98	62.85
30		Mode-1	121.60	0.320	7.01	43.81	6.67	52.97
31	S9_BI_ IR2_DF_X	Accl.	106.40	0.280	7.85	43.00	5.00	49.88
32		IS 1893	136.80	0.360	7.19	44.88	6.67	63.64
33		Mode-2	152.00	0.400	14.89	46.32	13.16	66.20
34	S9_BI_ IR2_DF_Y	Accl.	106.40	0.280	5.93	42.94	5.26	49.00
35		IS 1893	152.00	0.400	7.12	45.46	6.67	65.54
36		Mode-1	45.60	0.120	0.00	33.33	0.00	12.65
37	S9_BI_ IR3_DF_X	Accl.	106.40	0.280	5.82	42.97	4.88	50.61
38		IS 1893	136.80	0.360	6.89	44.61	6.52	64.94
39		Mode-2	152.00	0.400	10.55	45.87	9.76	68.41
40	S9_BI_ IR3_DF_Y	Accl.	106.40	0.280	5.42	42.87	4.88	47.89
41		IS 1893	152.00	0.400	6.42	45.13	6.12	63.68
42		Mode-1	15.20	0.040	0.00	0.00	0.00	0.00

Table 8. Different minimum to maximum ranges at performance point against three lateral loads

Building type & Setback type	Storey	Drift range %		EBDI range %		SBDI range %	
		X direction	Y direction	X direction	Y direction	X direction	Y direction
Regular	4	0.200	0.200	3.44-8.14	0.79-8.47	40.0-40.3	40.0-40.3
Irreg_Uni_IR1		0.200	0.20-0.24	3.23-8.06	2.07-11.1	40.0-40.2	40.0-41.9
Irreg_Uni_IR2		0.120	0.12-0.16	7.67-13.3	5.51-17.6	34.0-34.3	33.4-38.8
Irreg_Uni_IR3		0.120	0.12-0.16	9.90-14.1	5.40-5.46	33.3-33.4	33.3-37.5
Irreg_BI_IR2		0.08-0.12	0.04-0.12	0.00-12.5	0.00	25.0-33.3	0.00-37.8
Irreg_BI_IR3		0.08-0.12	0.04-0.12	8.61-9.95	0.00-6.84	25.0-33.3	25.0-33.3
Regular	6	0.32-0.36	0.32-0.36	5.21-6.95	5.64-7.58	43.9-44.7	43.9-44.8
Irreg_IR1		0.20	0.20	11.31-11.34	10.16-10.92	40.3	40.3
Irreg_IR2		0.32-0.40	0.36-0.44	0.00	0.00	43.7-45.0	37.5-45.4
Irreg_IR3		0.28-0.36	0.32-0.40	2.20-7.43	4.47-4.75	42.8-44.6	43.7-45.1
Irreg_BI_IR1		0.2-0.24	0.2-0.24	5.93-6.51	0.00-5.45	40.0-41.8	40.0-41.7
Irreg_BI_IR2		0.12	0.16-0.20	6.52-7.01	11.42-11.91	33.3	37.8-40.3
Irreg_BI_IR3		0.12-0.16	0.16-0.24	4.82-10.92	4.15-20.21	33.3-37.7	37.5-42.3
Regular	9	0.32-0.36	0.32-0.36	7.64-9.90	8.48-10.38	44.0-45.0	44.1-45.0
Irreg_IR1		0.32-0.40	0.36-0.44	0.00	0.00	43.7-45.0	44.4-45.4

Irreg_IR2		0.28-0.36	0.32-0.44	0.00-7.24	0.00-7.26	42.9-44.7	43.9-45.4
Irreg_IR3		0.28-0.36	0.32-0.40	4.65-5.80	5.87-8.20	42.9-44.6	43.9-45.2
Irreg_BI_IR1		0.28-0.36	0.32-0.36	8.28-14.57	7.01-11.77	42.9-45.3	43.8-44.8
Irreg_BI_IR2		0.28-0.40	0.12-0.40	7.19-14.89	0.00-7.12	43.0-46.3	33.3-45.5
Irreg_BI_IR3		0.28-0.40	0.04-0.40	5.82-10.55	0.00-6.42	42.9-45.8	0.00-45.1

5. Results and Discussion

In the present work, the torsion caused by the setback kind of vertical irregularity in the building generates surprising reactions during analysis. Standard 174 pushover curves are used to assess damage at various performance levels of the curve. Total of 58 graphs of drift versus energy based DI and 58 graphs of drift versus stiffness based DI have been generated to review the overall behaviour of various buildings shown in figures 11 and 12. The first hysteretic cycle is considered for damage estimation for various energies and initial and secant stiffness at different performance levels.

The standard pushover curve and stiffness degradation curve of storey 9 have shown in Figures 9 and 10. Both the DIs are calibrated with exiting methods of Powell and Allahabadi's (1988) [5] and Zameeruddin and K. Sanghle's (2017) [16], which were derived from nonlinear static analysis. Both proposed damage indices have shown good results. The pushover analysis results are verified with M. Zameeruddin's (2016) [1] research paper's 2D frame building example, and the results are almost matched. Sample calculation of S9_BI_IR1_DF_Accl type of building's EBDI and SBDI are shown in table no. 4 and 5 at various performance levels, and damage indices results are shown in Table 6. Table 3 shows a sample result of pushover analysis for the S9_BI_IR1_DF_ Acceleration- X dir._ case. The minimum to maximum drift limits are mentioned in table 8; they are well within the prescribed limits shown in table 2. Bidirectional setback types of 4 and 6-storey buildings have a vulnerable response compared to 9-storey buildings. The maximum energy-based DI at the performance point (P.P) is around 8.47 %, 7.58 % and 10.38 % for 4, 6 and 9-storey buildings, respectively. The maximum values of EBDI are adjusted to 17.6 %, 11.34 % and 8.20 % for 4, 6 and 9-storey irregular unidirectional setback types of buildings, respectively. While considering bidirectional setback types of buildings, values are adjusted to 12.5 %, 20.21 % and 14.89 % for three distinct buildings. The maximum stiffness-based DI at the P.P ranges from 40 % to 45 % for all three heights. In case of unidirectional buildings these values are adjusted to 33.3 % to 41.9 %, 37.5 % to 45.4 % and 42.9 % to 45.4 % for 4, 6 and 9 storey buildings respectively. While considering bidirectional setback types, values vary between 25 % to 37.8 %, 33.3 % to 42.3 % and 33.3 to 45.8 % for 4, 6 and 9-storey buildings, respectively.

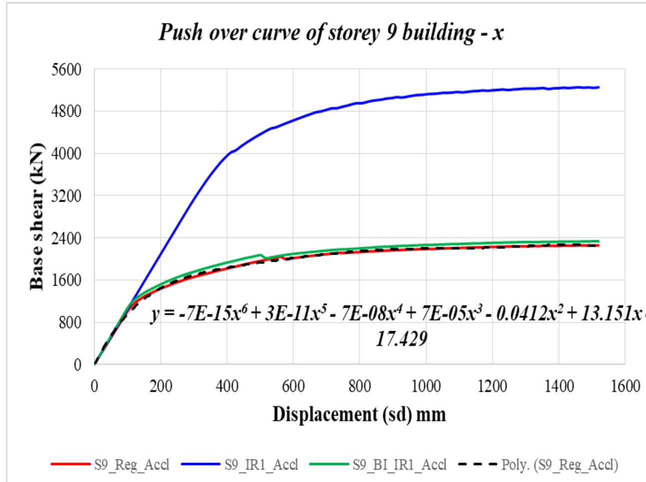

Fig. 9 Pushover curve for different storey 9 building case

A performance point is reached in all conditions within the drift limit of the damage control range (DCR) level. While computing the stiffness damage index, the performance point is reached in all cases when the stiffness damage index was extended by roughly 45%, as indicated in table 7. A comparison of proposed damage indices with existing damage indices is also shown in table 7. Due to the pushover analysis, the building suffered greater damage as the stiffness degraded. There is no noticeable change in drift range for any load patterns as the building's height increases.

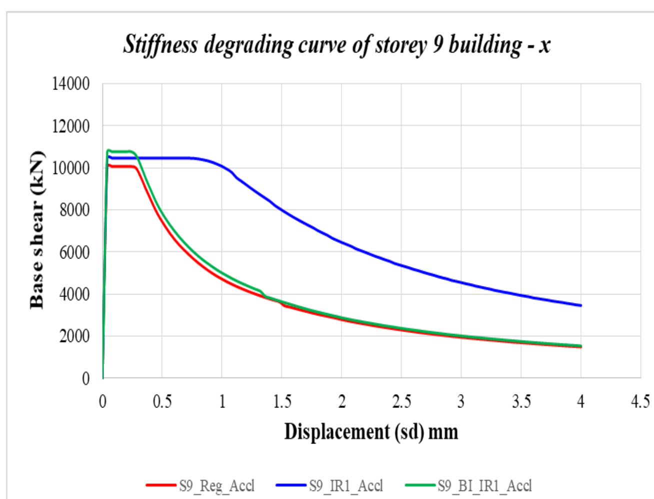

Fig. 10 Stiffness degradation curve for different storey 9 building case

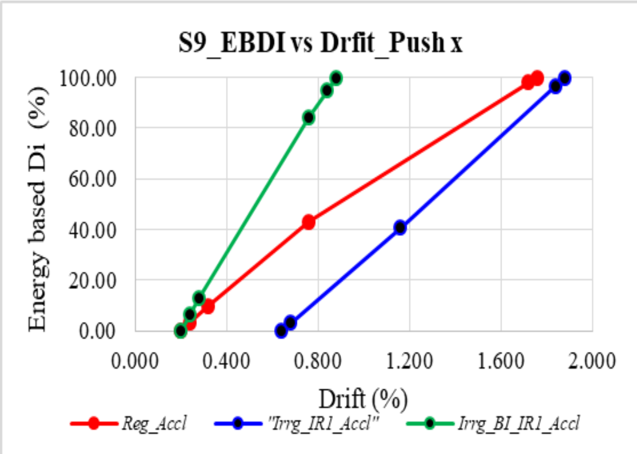

Fig. 11 EBDi vs Drift for various S9 buildings

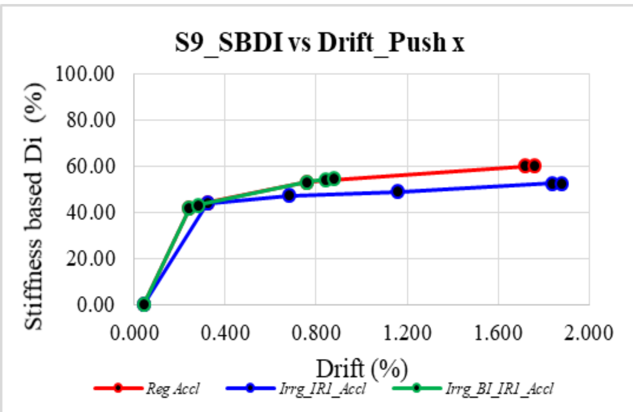

Fig. 12 SBDi vs Drift for various S9 buildings

Compared to the acceleration type of monotonic load with IS 1893, the mode type of monotonic load patterns is shown a higher drift.

6. Conclusion

The seismic performance of RC buildings with regular and irregular configurations was designed using the Indian seismic codes by performing linear static and dynamic analysis. Then, nonlinear static analysis was performed on them using three different types of monotonic loadings. Several attempts to estimate seismic damage indices have been made. However, most of them were based on regular or irregular 2D frames that did not respond well to unexpected effects due to irregularities. The current study is based on 3D vertical irregular buildings, showing that torsion generated the unanticipated nonlinear reaction and that torsion makes the building more vulnerable. The following conclusions may be drawn from this research.

The analysis of 3D vertical irregular buildings provides acceptable outcomes, and both DI methods have been proven capable of properly estimating the damage to 3D irregular buildings. Load patterns are the most critical factors in absorbed energy and stiffness deterioration; thus, all three types of monotonic load patterns should be employed in evaluating damage at the point of performance. Damages may be calculated using damage indices at any position along the pushover curve. Estimating the damages for existing and proposed irregular buildings at any point along the curve is far more suitable and efficient. The proposed stiffness damage index can calculate the damage value at the intended performance levels, taking into account all nonlinear responses at each incremental step of the pushover and accounting for the cumulative effects of degrading stiffness that were previously unaccounted for by existing damage estimations. The results of the pushover curve in all situations indicate that the drift is well below permissible limits under current standards. Although the force-based design procedure provided by the Indian seismic code appears to be successful for regular frames, it cannot meet the life safety performance level criteria in irregular frames with setbacks along their height. In particular, short buildings with unidirectional and bidirectional setbacks induced a susceptible response, demanding more attention for deigning to achieve life safety performance. In the past, the majority of them collapse under design earthquakes. As a result, it appears that criteria in codes 1893-2016 need to be improved to identify and propose alternative indications and procedures for estimating the seismic behaviour of vertically irregular buildings.

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