PROGRESSIVE COLLAPSE ANALYSIS OF RC STRUCTURE RESTING ON SLOPING GROUND

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ABSTRACT

Progressive collapse is the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it. The phenomenon is of particular concern since progressive collapse is often (though not always) disproportionate, i.e., the collapse is out of proportion to the event that triggers it. Thus, in structures susceptible to progressive collapse, small events can have catastrophic consequences. These efforts tended to focus on improving redundancy and alternate load paths, to ensure that loss of any single component would not lead to a general collapse. But in fact, redundancy is only one of the ways of reducing susceptibility to disproportionate collapse. Improved local resistance for critical components and improved continuity and interconnection throughout the structure (which can improve both redundancy and local resistance) can be more effective than increased redundancy in many instances. Through an appropriate combination of improved redundancy, local resistance and interconnection, is possible to greatly reduce the susceptibility of buildings to disproportionate collapse. In the present study linear static and nonlinear static analysis were done for special RC moment-resisting frames by ETAB software using various lateral load patterns. Demand capacity ratio (DCR) of special moment resisting frame of 16 storey structure are evaluated as per the GSA guidelines, and measurable parameters that could be used to predict the structural behavior toward possible progressive collapse.

Key words: Building, DCR, disproportionate, Progressive collapse, Pushover analysis.

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1. INTRODUCTION

Progressive collapse of a structure is defined as "a situation where a local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence, the total damage is disproportionate to the original cause". There are many cases of progressive collapse of buildings that occurred in the past due to different reasons. The first case that triggered special attention in the engineering community was the progressive collapse of a part of the 22-storey Ronan C apartment building in London, England in 1968. A gas explosion at the 18th floor of the building triggered the collapse of the corner slabs at the upper floors (above the 18th floor) that was followed by the collapse of all corner slabs of the building. The progressive collapse of structural building is initiated when one or more vertical load carrying members (typically columns) are removed.

Once a column is removed due to a vehicle impact, fire, earthquake or any other man-made or natural hazards, the buildings weight (gravity load) gets transferred to neighboring columns in the structure. If these columns are not properly designed to resist and redistribute the additional gravity load that part of the structure fails. The vertical load carrying elements of the structure continue to fail until the additional loading is stabilized. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact. A progressive collapse analysis is required to determine the capability of a structure to resist abnormal loadings. The progressive failure analysis method is threat independent, in the sense that it is initially assumed that some type of short duration abnormal loading has caused local damage represented by the removal of one or more critical members.

2. GSA guidelines

The General Service Administration (GSA) progressive collapse guideline provides a detailed methodology and performance criteria needed to assess the vulnerability of new and existing buildings to progressive collapse. For atypical or unsymmetrical framed structures in elevation, the following analysis cases should be considered (GSA 2003).

Exterior consideration

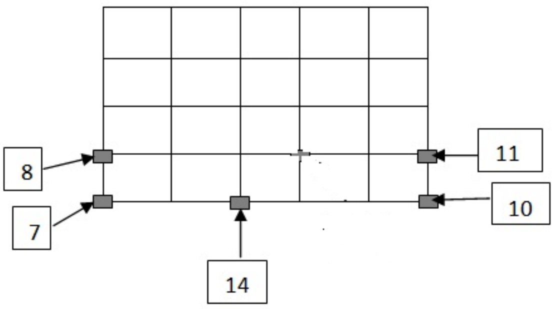

Fig. 1 Exterior consideration cases of column removal.

Interior consideration

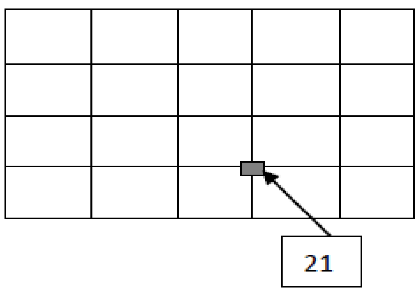

Fig. 2 Interior consideration case of column removal.

The following exterior analysis cases should be considered.

1. Analyze for the instantaneous loss of a column for one floor above grade (4 storey) located at corner of the short side of the building(C-7).
2. Analyze for the instantaneous loss of a column for one floor above grade (4 storey) located at or near the middle of the short side of the building(C-8).
3. Analyze for the instantaneous loss of a column for one floor above grade (1 storey) located at corner of the short side of the building(C-10).
4. Analyze for the instantaneous loss of a column for one floor above grade (1 storey) located at or near the middle of the short side of the building(C-11).
5. Analyze for the instantaneous loss of a column for one floor above grade (3 storey) located at or near the middle of the long side of the building(C-14).
6. Analyze for the instantaneous loss of a column for one floor above grade (1 storey) located at or near interior of the long side of the building(C-21).

A separate analysis must be performed for each case. While performing a static linear analysis, the vertical load case applied to the structure is as Load = (DL + 0.25LL) (1)
Where, DL = Dead Load, and LL = Live Load.

3. Analysis procedure

Linear static analysis

In the linear static analysis column is removed from the location being considered and linear static analysis with the gravity load given by Eq.1 imposed on the structure has been carried out. From the analysis results demand at critical locations are obtained and from the original seismically designed section the capacity of the member is determined. Check for the DCR in each structural member is carried out. If the DCR of a member exceeds the acceptance criteria in shear and flexure, the member is considered as failed. The demand capacity ratio calculated from linear static procedure helps to determine the potential for progressive collapse of building.

Nonlinear static analysis

Nonlinear static analysis procedure is carried out in the following steps using ETAB 9.7 Software.

1. Build a finite-element computer model.
2. Define and assign nonlinear plastic hinge properties, to beams and columns.
3. Apply static load combination.
4. Perform nonlinear static analysis.

5. Verify and validate the results based on hinge formation.

4. Modeling of building

The building for the study is sixteen storey unsymmetrical R.C. building in elevation. The structure consists of five bays of 5 m in the longitudinal direction and three bays of 5 m in the transverse direction. Column sizes are taken as 600x800mm and 600x600mm. Beam size taken as 300x550mm. Slab thickness125mm and wall thickness as 200mm. Loading considered on the building for the study are as follows.

Dead load

Self weight of the structural elements

Floor finish = 1.5 kN/m^2 and

Wall load on all beams is 12.4 kN/m

Live load taken as 3.0 kN/m^2

Seismic loading as per IS: 1893 2002

Zone II, III, IV &V

Soil type II,

Response Reduction Factor = 5

Importance factor =1.5

The characteristic compressive strength of concrete (fck) is 25 N/mm^2 & 30 N/mm^2. Yield strength of reinforcing steel (fy) is 415 N/mm^2 & 500 N/mm^2. Analysis and design of building for the loading is performed in the ETAB9.7. Sixteen storey building is designed for seismic loading in ETAB 9.7 according to the IS 456:2000. Based on the reinforcement demand capacity ratio is calculated.

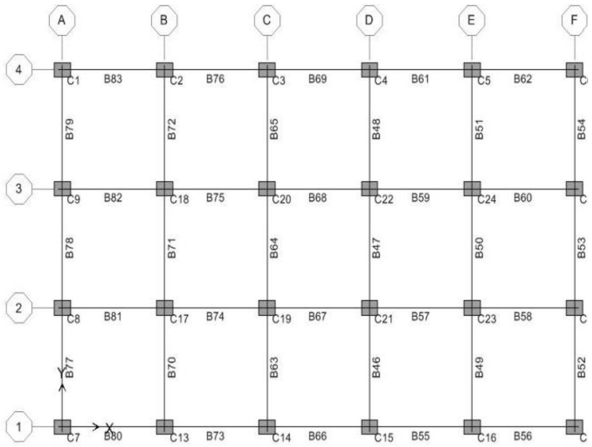

Fig.3 Plan of the building

To evaluate the potential for progressive collapse of a sixteen storey unsymmetrical reinforced concrete building using the linear static analysis six column removal conditions is considered. First building is designed in ETAB 9.7 for the IS: 1893 2002 load combinations. Then separate linear static analysis is performed for each case of column removal. Demand capacity ratio for flexure at all storeys' is calculated for all six cases of column failure.

Acceptance criterion for progressive collapse

The GSA proposed the use of the Demand–Capacity Ratio (DCR), the ratio of the member force and the member strength, as a criterion to determine the failure of main structural members by the linear analysis procedure (GSA 2003).

$$DCR = \frac{Q_{UD}}{Q_{CE}}$$

Where,

QUD = Acting force (demand) determined in member or connection (moment, axial force, shear, and possible combined forces).

QCE = Expected ultimate, un-factored capacity of the member and connection (Moment, axial force, shear and possible combined forces).

The allowable DCR values for primary and secondary structural elements are:

• DCR < 2.0 for symmetrical structural configurations.

• DCR < 1.5 for unsymmetrical structural configurations.

5. Methods of preventing disproportionate collapse

1. Redundancy or alternate load paths, where the structure is designed such that if any one component fails, alternate paths are available for the load in that component and a general collapse does not occur.
2. Local resistance, where susceptibility to progressive/disproportionate collapse is reduced by providing critical components that might be subject to attack with additional resistance to such attacks
3. Interconnection or continuity, which is, strictly speaking, not a third approach separate from redundancy and local resistance, but a means of improving redundancy or local resistance or both

6. Graphical representation of DCR

After getting all the DCR values of beam for critical cases of column removal, for all zones graph is plotted Storey Vs DCR'S.

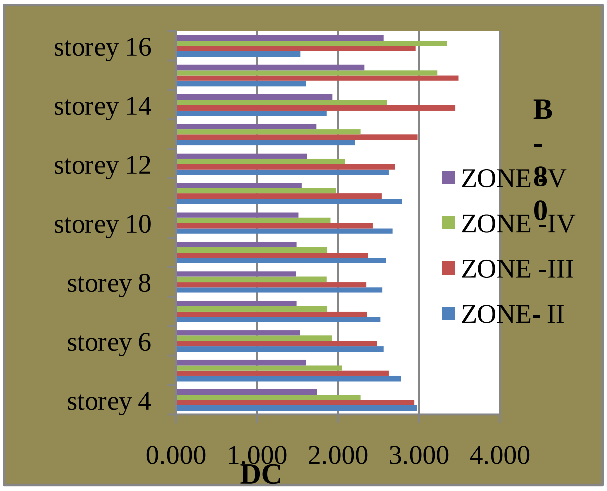

Fig.4 Corner of the short side column eliminated C-7

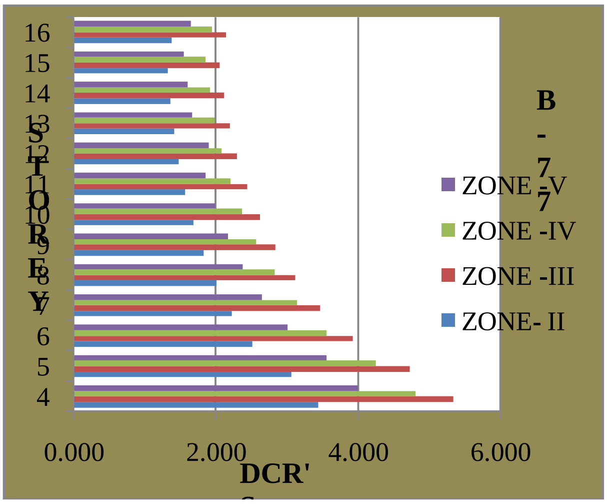

Fig.5 Corner of the short side column eliminated C-7

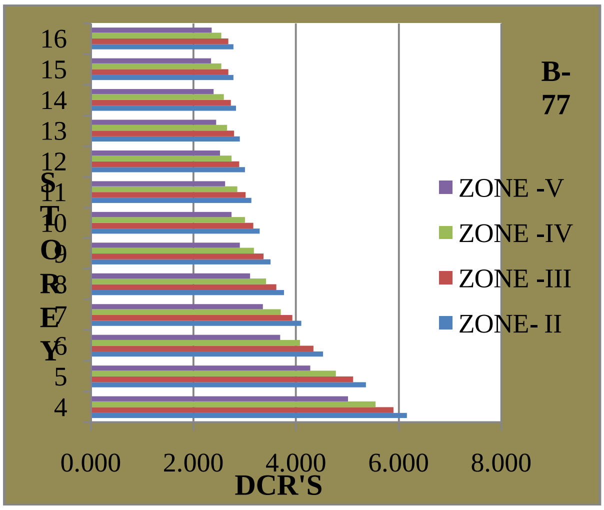

Fig.6 Middle of the short side column eliminated C-8

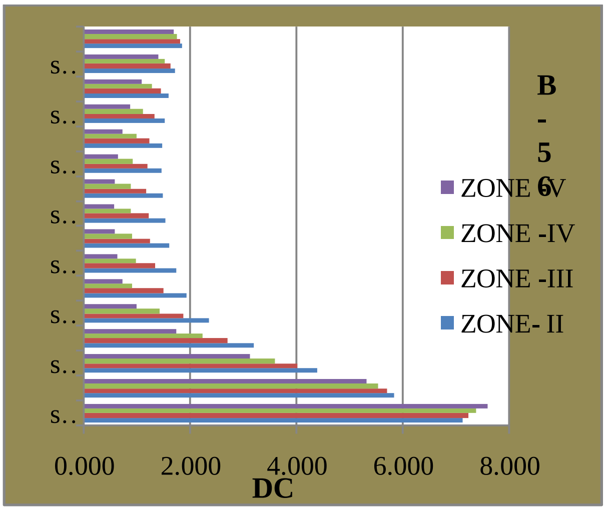

Fig.9 Corner of the short side column eliminated C-10

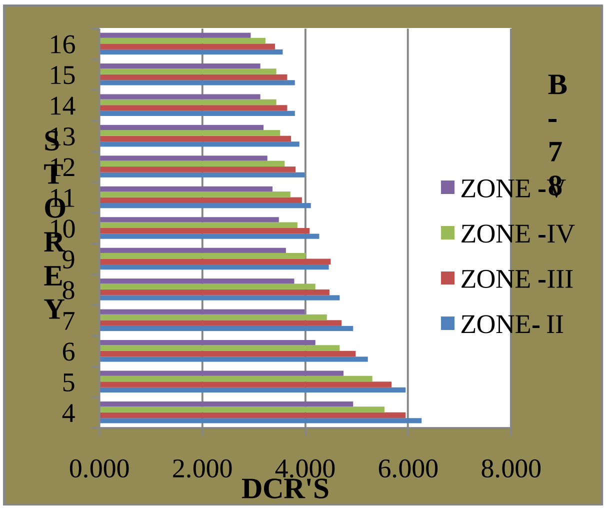

Fig.7 Middle of the short side column eliminated C-8

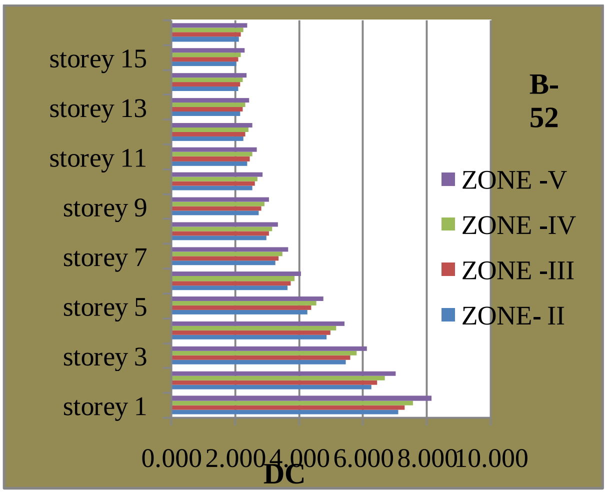

Fig.10 Corner of the short side column eliminated C-10

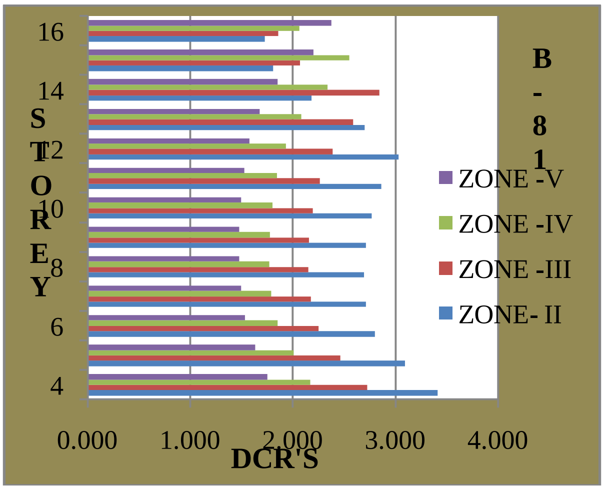

Fig.8 Middle of the short side column eliminated C-8

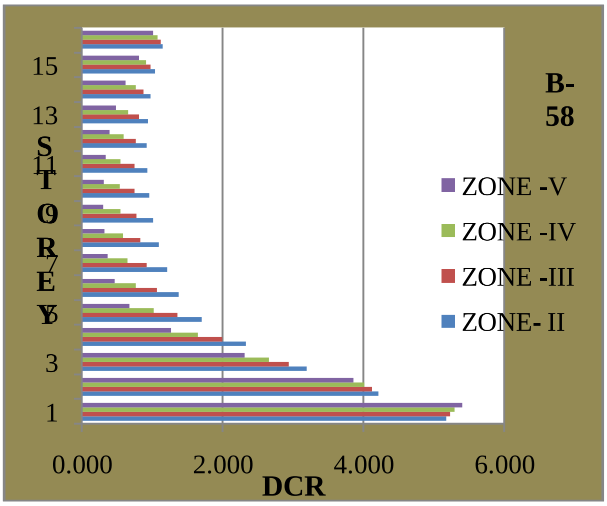

Fig.11 Middle of the short side column eliminated C-11

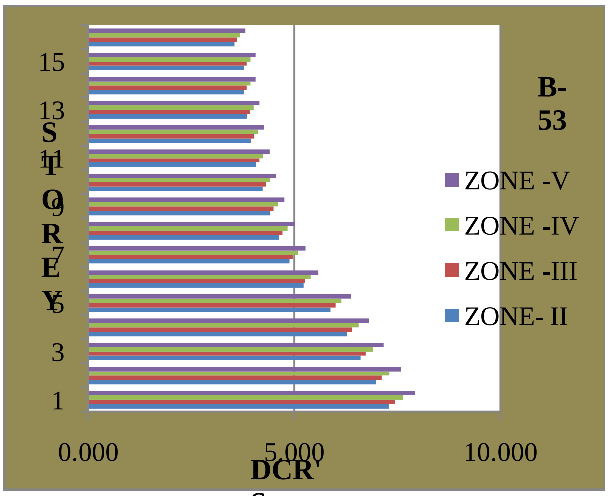

Fig.12 Middle of the short side column eliminated C-11

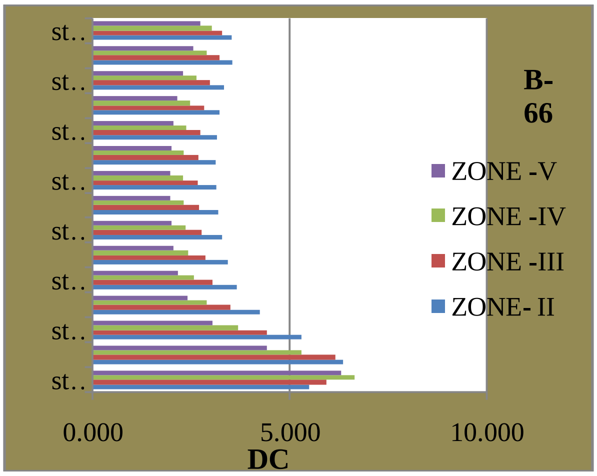

Fig.15 Middle of the long side column eliminated C-14

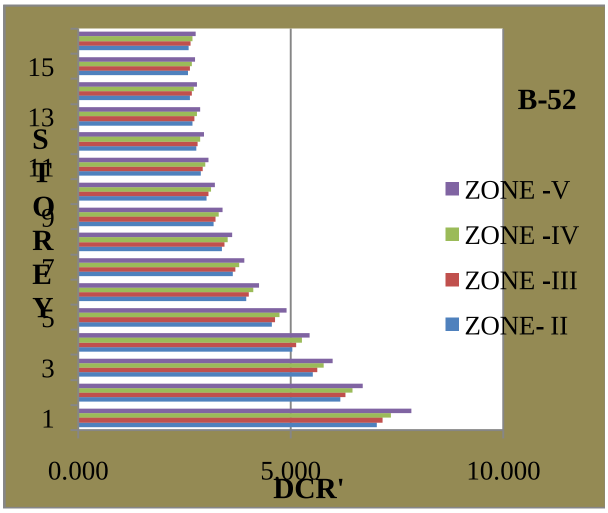

Fig.13 Middle of the short side column eliminated C-11

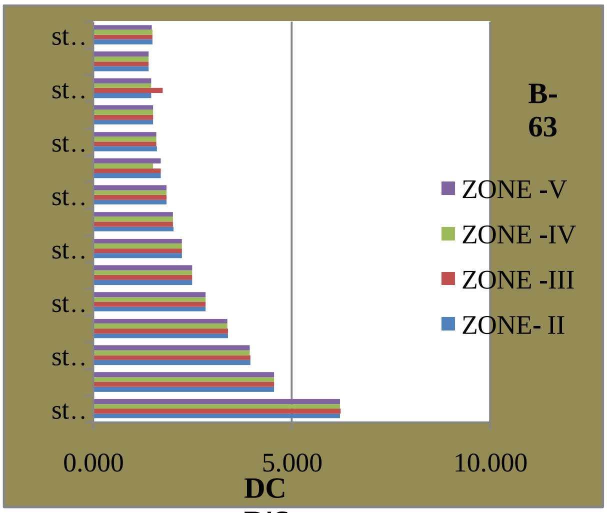

Fig.16 Middle of the long side column eliminated C-14

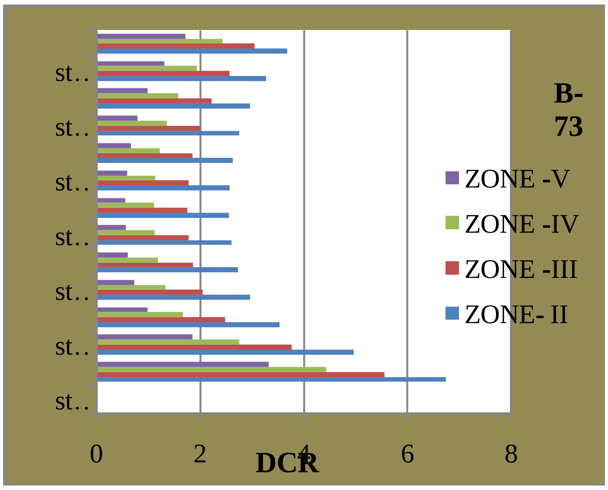

Fig.14 Middle of the long side column eliminated C-14

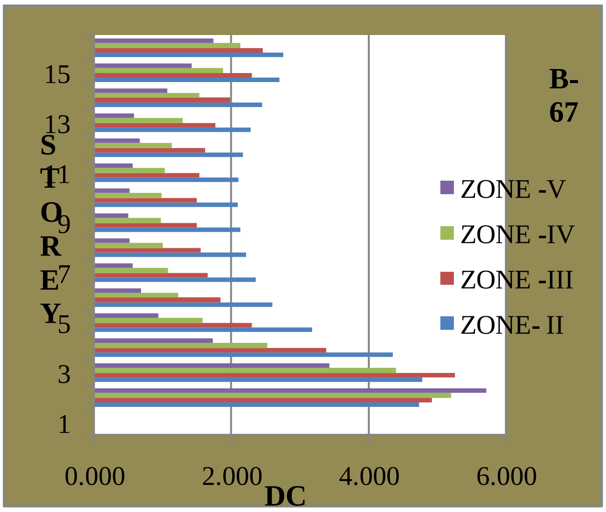

Fig.17 Interior of the long side column eliminated C-21

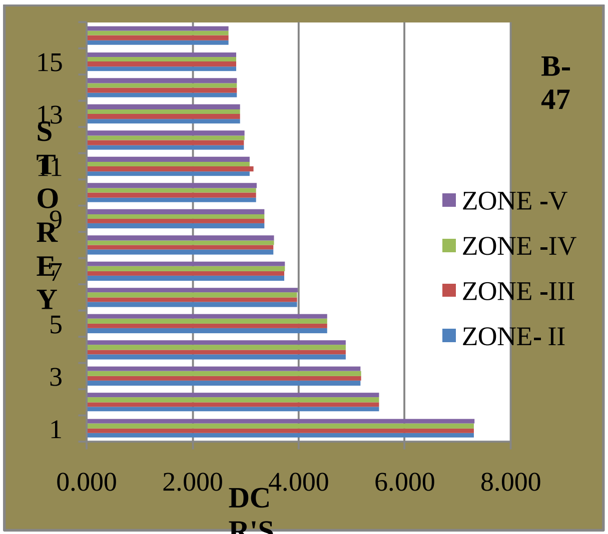

Fig.18 Interior of the long side column eliminated C-21

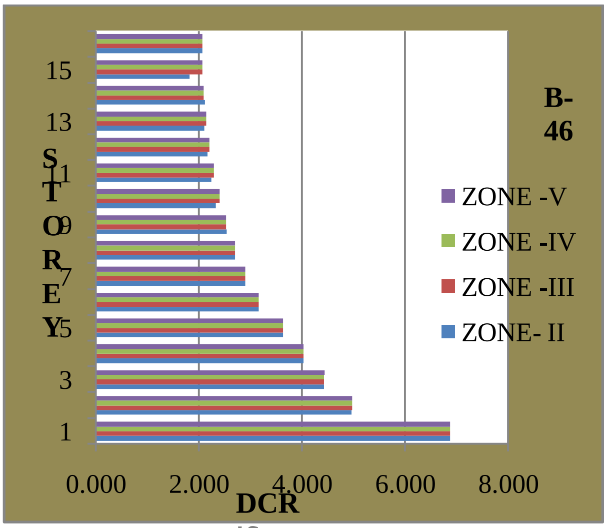

Fig.20 Interior of the long side column eliminated C-21

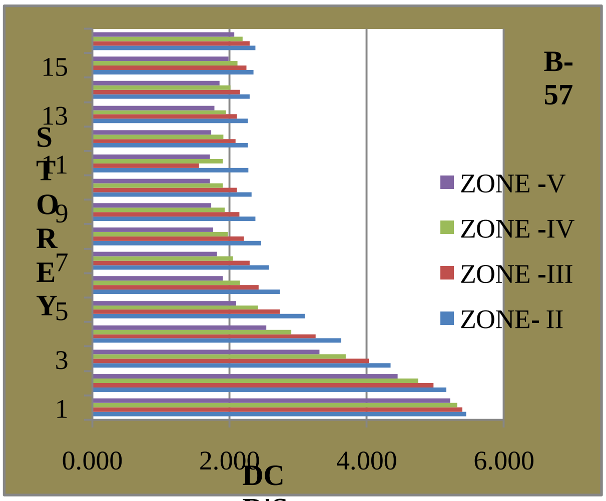

Fig.19 Interior of the long side column eliminated C-21

7. Nonlinear static analysis

The purpose of pushover analysis that evaluate the expected performance of structural systems by estimating performance of a structural system by estimating its strength and deformation demands in design earthquakes by means of static inelastic analysis, and comparing these demands to available capacities at the performance levels of interest.

Nonlinear static analysis is widely used to analyze a building for a lateral load and is known as ‘‘pushover analysis”. It increases applied loads step-by-step until maximum load is attained or maximum displacement is attained. For nonlinear analysis hinge properties and user-defined hinge properties can be assigned to frame elements. When user-defined hinge properties are assigned to a frame element, the program automatically creates a generated hinge property for each and every hinge.

8. Capacity spectrum method

This method is to develop appropriate demand and capacity spectra for the structure and to determine their intersection. During this process, performance of each structural component is also evaluated. The structure capacity is represented by a pushover curve often termed as capacity curve. The most convenient way to plot the force displacement curve is by tracking the base shear and roof displacement.

9. Displacement coefficient method

This method is to find target displacement which is the maximum displacement that the structure is likely to experience during the design earthquake.

Pushover analysis in X-direction

Table 1 Pushover capacity/demand comparison for various building column removal

	Column-7				Column-8				Column-14			
Step	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)
0	0.000	0.000	0.124	0.321	0.000	0.000	0.111	0.358	0.000	0.000	0.121	0.329
1	0.021	0.055	0.124	0.321	0.022	0.072	0.111	0.358	0.020	0.054	0.121	0.329
2	0.032	0.080	0.119	0.295	0.034	0.098	0.103	0.299	0.034	0.089	0.117	0.304
3	0.080	0.119	0.114	0.169	0.061	0.121	0.098	0.195	0.061	0.120	0.108	0.213
4	0.215	0.165	0.142	0.109	0.124	0.150	0.113	0.136	0.115	0.154	0.115	0.154
5	0.369	0.193	0.167	0.087	0.273	0.187	0.145	0.099	0.266	0.197	0.142	0.105
6	0.378	0.194	0.169	0.087	0.383	0.204	0.162	0.086	0.354	0.215	0.155	0.094
7	-	-	-	-	0.383	0.201	0.162	0.085	0.365	0.216	0.157	0.093
8	-	-	-	-	0.383	0.202	0.162	0.085	0.365	0.215	0.157	0.092
9	-	-	-	-	-	-	-	-	0.365	0.215	0.157	0.092
10	-	-	-	-	-	-	-	-	0.365	0.214	0.157	0.092

Table 2 Pushover capacity/demand comparison for various building column removal

	Column-10				Column-11				Column-21			
Step	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)
0	0.000	0.000	0.120	0.331	0.000	0.000	0.115	0.346	0.000	0.000	0.111	0.357
1	0.019	0.051	0.120	0.331	0.024	0.072	0.115	0.346	0.022	0.070	0.111	0.357
2	0.029	0.079	0.120	0.332	0.033	0.096	0.110	0.318	0.037	0.104	0.104	0.297
3	0.053	0.110	0.106	0.221	0.049	0.113	0.100	0.232	0.060	0.129	0.099	0.213
4	0.124	0.152	0.118	0.145	0.130	0.155	0.115	0.137	0.117	0.162	0.109	0.150
5	0.267	0.190	0.144	0.103	0.265	0.187	0.143	0.101	0.270	0.203	0.138	0.104
6	0.380	0.211	0.162	0.090	0.392	0.208	0.163	0.086	0.346	0.219	0.150	0.095
7	0.381	0.209	0.161	0.089	-	-	-	-	0.370	0.223	0.154	0.092
8	0.382	0.210	0.162	0.089	-	-	-	-	-	-	-	-
9	0.000	0.000	0.120	0.331	-	-	-	-	-	-	-	-

Where,

Sa(C), Sd(C) - capacity spectrum and Sa (D), Sd (D) - demand spectrum.

Performance point can be obtained by superimposing capacity spectrum and demand spectrum and the intersection point of these two curves is performance point. Fig 21-26 shows superimposing demand spectrum and capacity spectrum.

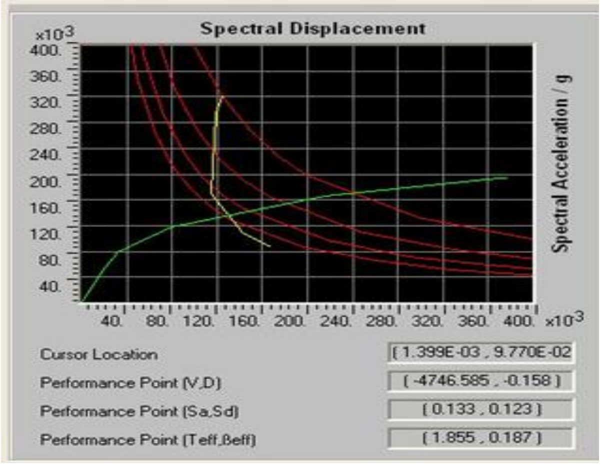

Fig.21 Performance point (V, D) curve for C-7

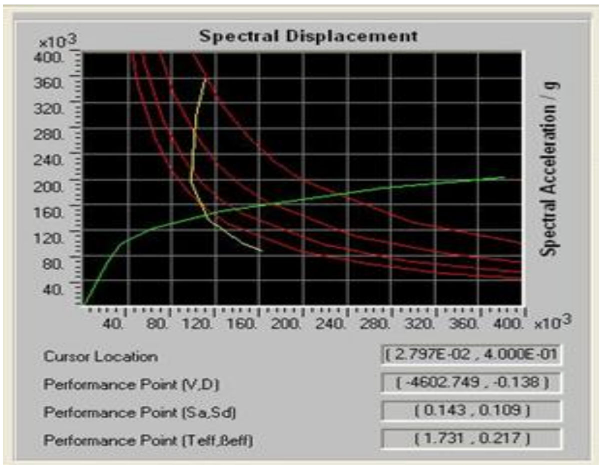

Fig.22 Performance point (V, D) curve for C-8

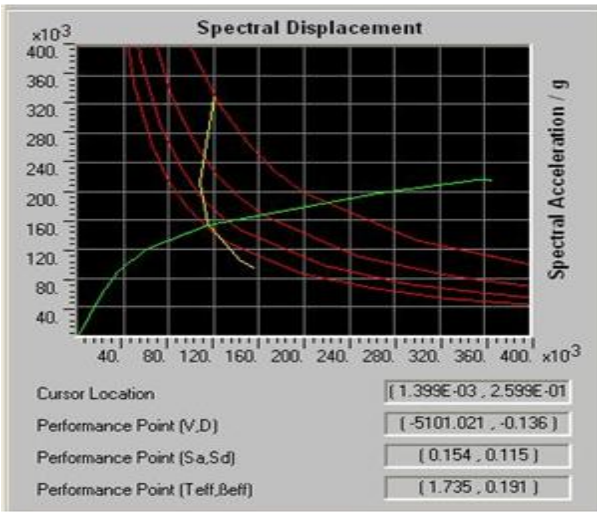

Fig.23 Performance point (V, D) curve for C-14

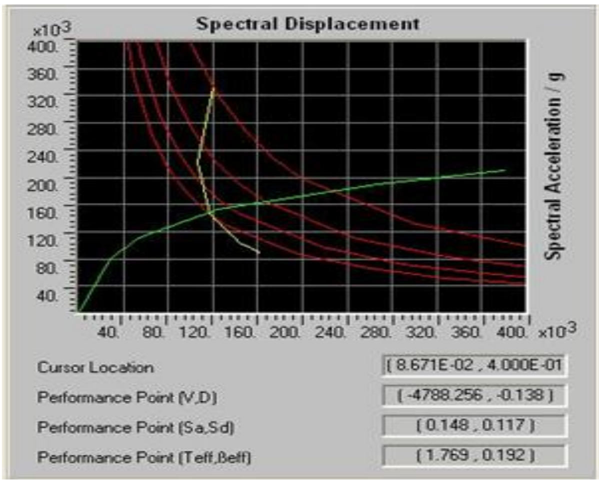

Fig.24 Performance point (V, D) curve for C-10

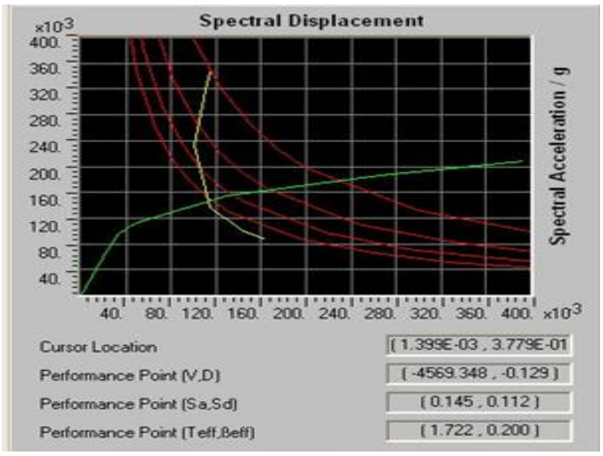

Fig.25 Performance point (V, D) curve for C-11

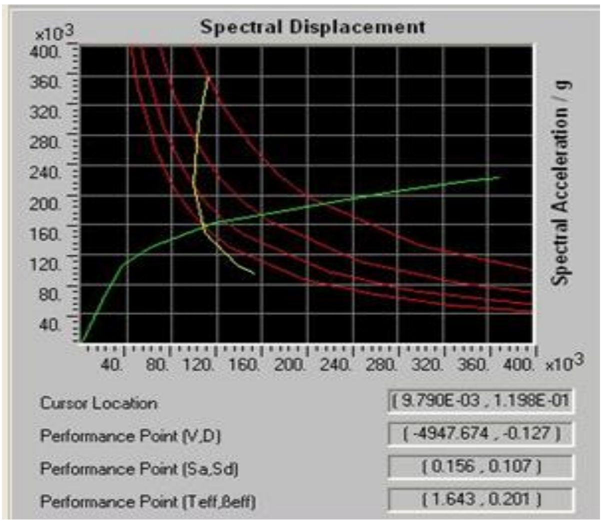

Fig.26 Performance point (V, D) curve for C-21

Pushover analysis in Y-direction

Table 3 Pushover capacity/demand comparison for various building column removal

	Column-7				Column-8				Column 14			
Step	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)
0	0.000	0.000	0.129	0.308	0.000	0.000	0.133	0.300	0.000	0.000	0.123	0.323
1	0.025	0.060	0.129	0.308	0.029	0.065	0.133	0.300	0.029	0.076	0.123	0.323
2	0.038	0.082	0.119	0.253	0.044	0.090	0.123	0.251	0.041	0.096	0.114	0.269
3	0.075	0.102	0.115	0.156	0.077	0.112	0.117	0.170	0.059	0.108	0.106	0.193
4	0.164	0.128	0.139	0.108	0.179	0.140	0.138	0.108	0.129	0.130	0.121	0.122
5	0.331	0.155	0.174	0.082	0.349	0.167	0.172	0.082	0.295	0.158	0.160	0.086
6	0.353	0.158	0.178	0.080	0.355	0.168	0.173	0.082	0.375	0.168	0.175	0.078
7	0.353	0.156	0.178	0.079	0.355	0.166	0.173	0.081	0.375	0.166	0.175	0.077
8	0.354	0.156	0.178	0.079	0.355	0.165	0.173	0.080	0.376	0.166	0.175	0.078
9	0.355	0.157	0.178	0.079	0.356	0.166	0.173	0.080	0.376	0.167	0.175	0.078
10	0.355	0.157	0.178	0.079	0.356	0.166	0.173	0.080	0.377	0.167	0.175	0.077
11	0.355	0.156	0.178	0.078	0.357	0.166	0.173	0.080	0.377	0.166	0.175	0.077
12	0.356	0.156	0.178	0.078	0.358	0.166	0.173	0.080	0.378	0.166	0.175	0.077
13	0.356	0.156	0.178	0.078	0.358	0.166	0.173	0.080	0.379	0.167	0.176	0.077
14	0.357	0.156	0.179	0.078	0.358	0.165	0.173	0.080	0.379	0.166	0.176	0.077
15	0.358	0.156	0.179	0.078	0.360	0.165	0.173	0.080	0.380	0.166	0.176	0.077
16	0.361	0.156	0.179	0.078	0.000	0.000	0.133	0.300	0.380	0.166	0.176	0.077
17	0.000	0.000	0.129	0.308	-	-	-	-	0.000	0.000	0.123	0.323
18	0.025	0.060	0.129	0.308	-	-	-	-	-	-	-	-

Table 4 Pushover capacity/demand comparison for various building column removal

	Column-10				Column-11				Column-21			
Step	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)	Sd(C)	Sa(C)	Sd(D)	Sa(D)
0	0.000	0.000	0.122	0.325	0.000	0.000	0.117	0.339	0.000	0.000	0.125	0.318
1	0.037	0.099	0.122	0.325	0.033	0.095	0.117	0.339	0.031	0.079	0.125	0.318
2	0.048	0.116	0.113	0.276	0.043	0.112	0.107	0.280	0.042	0.098	0.116	0.270
3	0.071	0.125	0.103	0.181	0.069	0.126	0.100	0.181	0.064	0.114	0.108	0.193
4	0.142	0.142	0.119	0.120	0.139	0.146	0.117	0.123	0.130	0.137	0.120	0.127
5	0.299	0.166	0.156	0.086	0.300	0.172	0.154	0.088	0.293	0.166	0.157	0.089
6	0.381	0.176	0.170	0.079	0.366	0.180	0.165	0.082	0.379	0.177	0.172	0.080
7	0.381	0.174	0.170	0.078	0.367	0.178	0.166	0.080	-	-	-	-
8	0.381	0.174	0.171	0.078	0.367	0.178	0.166	0.080	-	-	-	-
9	0.381	0.173	0.171	0.077	0.368	0.178	0.166	0.080	-	-	-	-
10	0.382	0.173	0.171	0.078	0.372	0.179	0.166	0.080	-	-	-	-
11	0.383	0.174	0.171	0.078	0.000	0.000	0.117	0.339	-	-	-	-
12	0.387	0.174	0.171	0.077	0.033	0.095	0.117	0.339	-	-	-	-
13	0.000	0.000	0.122	0.325	0.043	0.112	0.107	0.280	-	-	-	-
14	0.037	0.099	0.122	0.325	-	-	-	-	-	-	-	-

Where,

Sa(C), Sd(C) - capacity spectrum and Sa (D), Sd (D) - demand spectrum.

Performance point can be obtained by superimposing capacity spectrum and demand spectrum and the intersection point of these two curves is performance point. Fig 27-32 shows superimposing demand spectrum and capacity spectrum.

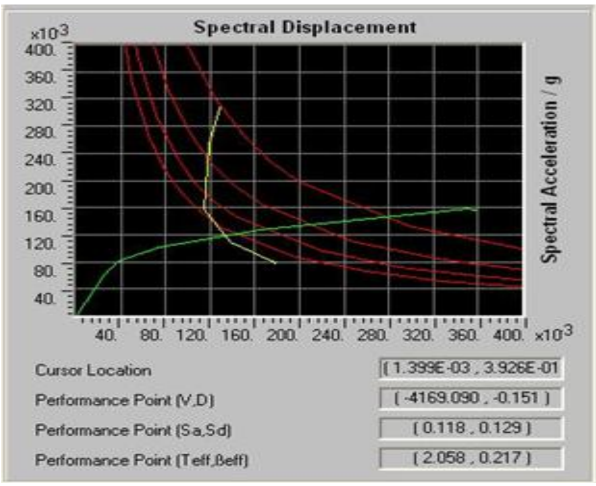

Fig.27 Performance point (V, D) curve for C-7

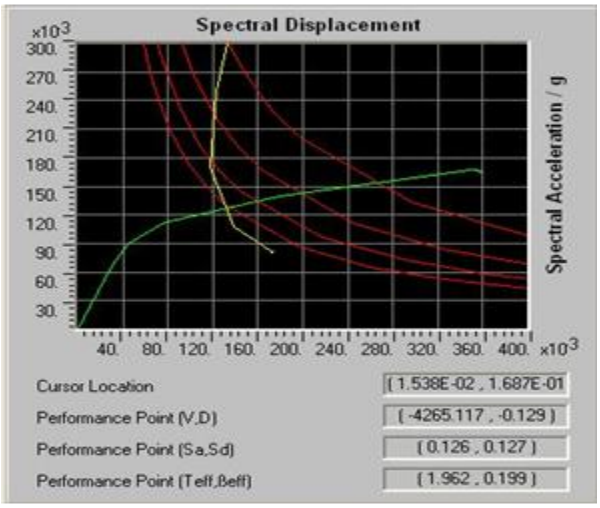

Fig.28 Performance point (V, D) curve for C-8

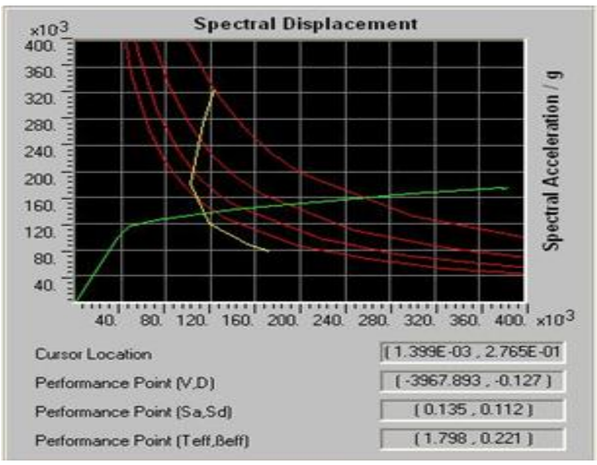

Fig.29 Performance point (V, D) curve for

C-14

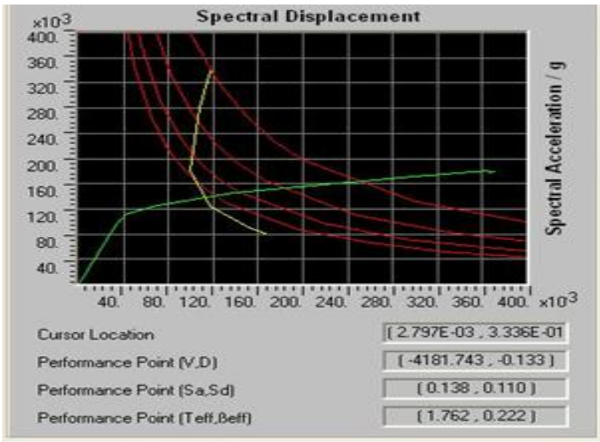

Fig.30 Performance point (V, D) curve for C-10

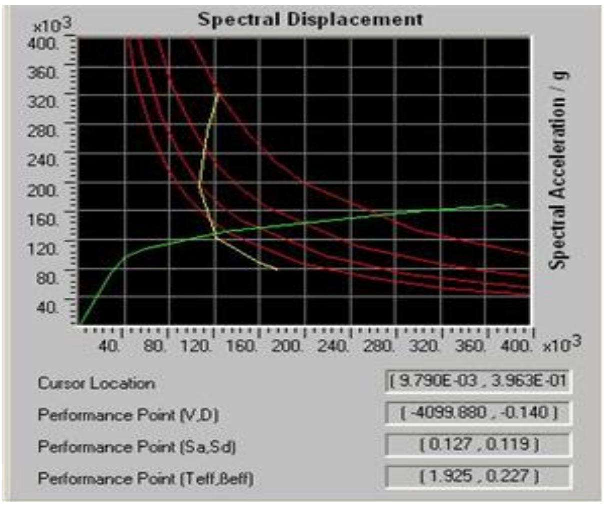

Fig.31 Performance point (V, D) curve for C-11

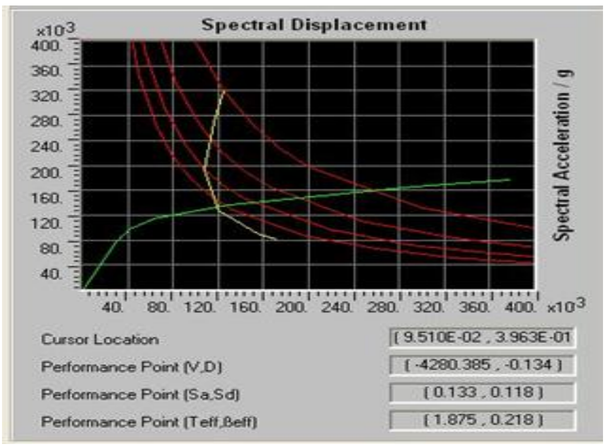

Fig.32 Performance point (V, D) curve for C-21

10. CONCLUSIONS

1. Seismically designed building has inherent ability to resist progressive collapse. The pushover analysis is a useful, but not in fallible, tool for accessing inelastic strength and deformation demands and for exposing design weaknesses.
2. To avoid the progressive collapse of beam and column, caused by failure of particular column, adequate reinforcement is required to limit the DCR within the acceptance criteria.
3. Non-linear static analysis reveals that hinge formation starts from the location having maximum demand capacity ratio.
4. Thus performance of pushover analysis primarily depends upon choice of material models included in the study.
5. The internal force resistance mechanisms of partially collapsed structures will be estimated more accurately based on the developed approach. This outcome will also enable one to treat an actual damaged structure, and support safe and effective rescue, recovery, and evacuation activities.

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