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PROGRESSIVE COLLAPSE OF DAMAGED STRUCTURES UNDER SEISMIC EXCITATION

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Abstract

During earthquake, it is quite often seen that two similar structures (building frames) constructed at the same time and at the same location behave differently; one may completely collapse and the other may remain standing. One of the possible causes is that a *progressive collapse* might have initiated by the earthquake for one, while for the other the progressive collapse is arrested at a certain damaged state. The initiation of progressive collapse in a structure is largely due to concentration of localized damages. In the present study, progressive collapse of a damaged building frame is investigated under seismic excitation. A ten story building frame is artificially damaged to create different damage scenarios having the same total damage expressed in terms of the total reduction of plastic moment capacities of beams and columns. Plastic analysis is carried out for each damage scenario in order to obtain the plastic moment capacities of damaged members by minimizing the collapse load factor subject to constraint that complete collapse mechanism is formed. This is achieved by using genetic algorithm. Push over analysis is carried for all cases, and the behavior of buildings at different stages of inelasticity including the final collapse are studied. The seismic demand curves represented by response spectra is superimposed on push over curves to find different performance points. The peak ground accelerations (PGA) of demand curves are adjusted to obtain the performance points to coincide with the collapse state of the capacity curves. The damage scenario, for which the capacity curve provides the performance point with lowest value of PGA, is most vulnerable to earthquake.

The results of the study show that i) there exists certain localized damage states for a building frame which may trigger progressive collapse leading to complete failure under an earthquake; ii) it is possible to identify these localized damage states using plastic analysis, genetic algorithm and push over analysis; iii) for an earthquake with a certain PGA level, similarly constructed buildings may have different progressive damages depending upon their initial damage states; iv) if the damage state of the building can be evaluated beforehand, vulnerability of building to collapse, under future earthquakes can be predicted using the methodology presented here.

Keywords: Pushover, Progressive Collapse, Plastic Analysis

1. Introduction

Progressive collapse is a phenomenon in which spread of initial localized damage in the structure leads to substantially large damage to the entire structure causing partial or complete collapse of the structure. There are several definitions of progressive collapse which has been summarized by Macilwraith [1]. Progressive collapse of a structure may be initiated by accidental or intentional localized damage such as those created by impact load, fire or explosion at one of the portion of structure. There can also be localized damage due to environmental and other time dependent phenomenon such as fatigue, shrinkage and creep. These effects can also lead to non-uniform or nearly uniform damages spread over the structure.

Progressive collapse of structure may be traced back to collapse of Ronan Point Apartment, London in 1968. A gas explosion on 18th floor caused a load bearing wall to collapse in turn initiated partial collapse of the structure [2]. Department of Defense (DoD) in "Minimum Antiterrorism Standards for Buildings" and General Services Administration(GSA) in "Progressive Collapse Analysis and Design Guidelines, have issued guidelines for analysis and design procedure to prevent progressive collapse of structure [3,4]. These guidelines mainly pertain to progressive collapse due to impact load or explosion.

Analysis techniques for progressive collapse are a) linear static analysis b) nonlinear static analysis c) linear time history analysis and d) nonlinear time history analysis. Most of the studies on progressive collapse are concerned with a sudden localized damage in the building due to external impact force. In all the analysis procedures, the main thrust is to randomly remove one or more vertical members from the structure to model the initial damage done by a random loading event. There can be instances where the structure may not completely fail in the random loading event. Instead, a few members sustain severe damage but the structures remain safe from the external excitation. The sudden removal of structural members has the same effect as the sudden application of the structural forces in in the direction opposite to transient dynamic response [5], As a consequence, forces redistribute in the system, and the damaged structure either comes to a new equilibrium point or the collapse occurs. While nonlinear dynamic time history analysis is believed to be the most realistic method to obtain the forces and deformation demands that develop in the system subsequent to initial damage, its application requires considerable skill, the computational demands are significant, and information necessary to perform the analysis correctly might not be available [6]. Therefore, an alternative nonlinear static analysis has been proposed and DoD/GSA guidelines provide details for this analysis. The guidelines are considered to be conservative, mainly for two reasons (i) damaged members usually have some residual capacity and (ii) beneficial effects of arching or catenary action are not considered [7].

Significant research has been carried out in recent past on the progressive collapse of building frames. Methods to design a structure such that progressive collapse of structure is prevented was first proposed by Ellingwood and Leyendecker [8]. In similar lines, different codes are framed so as to prevent progressive collapse of structure. Some of the recent includes those by Marjanishvili and Agnew who compared the analysis methods (LS, NS, ND, and linear dynamic) by analyzing a 9-story steel moment-resisting frame building in accordance with GSA guidelines [9]. To further elaborate design codes for progressive collapse, Menchel et al. compared four methods: linear static GSA, linear static DoD, nonlinear static DoD, and Load History– Dependent (LHD) [10].

Kwasniewski evaluated the progressive collapse potential of an eight-story steel frame structure under column removal using nonlinear dynamic finite element model based on the GSA guidelines [11].J. Kim et el, investigated the sensitivity of design variables of steel buildings subjected to progressive collapse [12]. Fu conducted nonlinear dynamic analysis of a three dimensional (3D) 20-story composite steel frame under consecutive column removal conditions using the general-purpose ABAQUS software [13]. Numerical modeling of semi-rigid connections using the SAP2000 software package have been discussed in detail by Bandyopadhyay et el [14]. They considered the geometric nonlinearity and debris loading.

The effects of seismic detailing on progressive collapse resistance of structures are discussed by Breen [15]. Some recent publications have also discussed relationships between seismic design/rehabilitation and progressive collapse resistance [1 - 3]. Corley and Hayes et al. have pointed out positive impacts of seismic resistance on progressive collapse resistance. In context of Murrah Federal Building [16, 17]

There is no literature exclusively on progressive collapse of structures under earthquake forces which is defined as spread of some initial localized damage in the structure due to earthquake loading to partial or complete collapse of the structure. The localized damage in the structure may be caused due to environmental effects or other accidental reasons than the environment effects. It is quite commonly seen that during the earthquake, two identical buildings built at same time and at the same site behaved differently; one may collapse and the other may survive with some damages. The reasons for the collapse of the former may be attributed to the development of some significant localized damages caused due to the reasons mentioned above. For the latter, nearly uniform damage, rather than high localized damage, may have taken place due to the same reasons. Progressive collapse under earthquake is different than the progressive collapse of structures reported in the literature in the sense that the former is a progressive collapse under the lateral loads, while the latter involves progressive collapse under the vertical loadings. Accordingly, the push over analysis which is carried out investigating the progressive collapse is different for the two cases.

In this paper, progressive collapse of damaged structures under earthquake loading is investigated. A ten story building frame is artificially damaged to create different damage scenarios. For each damage scenarios, a plastic analysis of the frame is carried out in order to obtain the plastic moment capacities of the damaged members such that minimum collapse load factor is achieved with a constraint that full collapse mechanism is formed. This is accomplished by using genetic algorithm. Push over analysis is then carried out for all the cases, to obtain the capacity curves. The seismic demand curves represented by response spectra are superimposed on the push over curves to find performance points. The peak ground acceleration (PGA) of the demand curves are adjusted to obtain the performance points coinciding with the collapse states. The damage scenarios which gives the least value of PGA to get the desired performance level is most vulnerable to progressive collapse to failure for the response spectrum consistent earthquake.

2. Methodology

Different damage scenarios of a building frame is simulated using plastic analysis and genetic algorithm. For this purpose, a ten story building with 3 bays is considered and different damage scenarios as shown in Figure 1(a-e) are created. In the encircled portion of the structure, plastic moment capacity (M_i^p) of beams and columns are reduced by various percentage compared to the rest of the structure. Total percentage reduction of plastic moment capacities remains the same for all cases. Apart from the above damage scenarios, another damage scenario (called reference damage state) is created by uniform reduction of plastic moment capacities of beams and columns.

For each damage scenarios, a plastic analysis is carried out by combining different sway

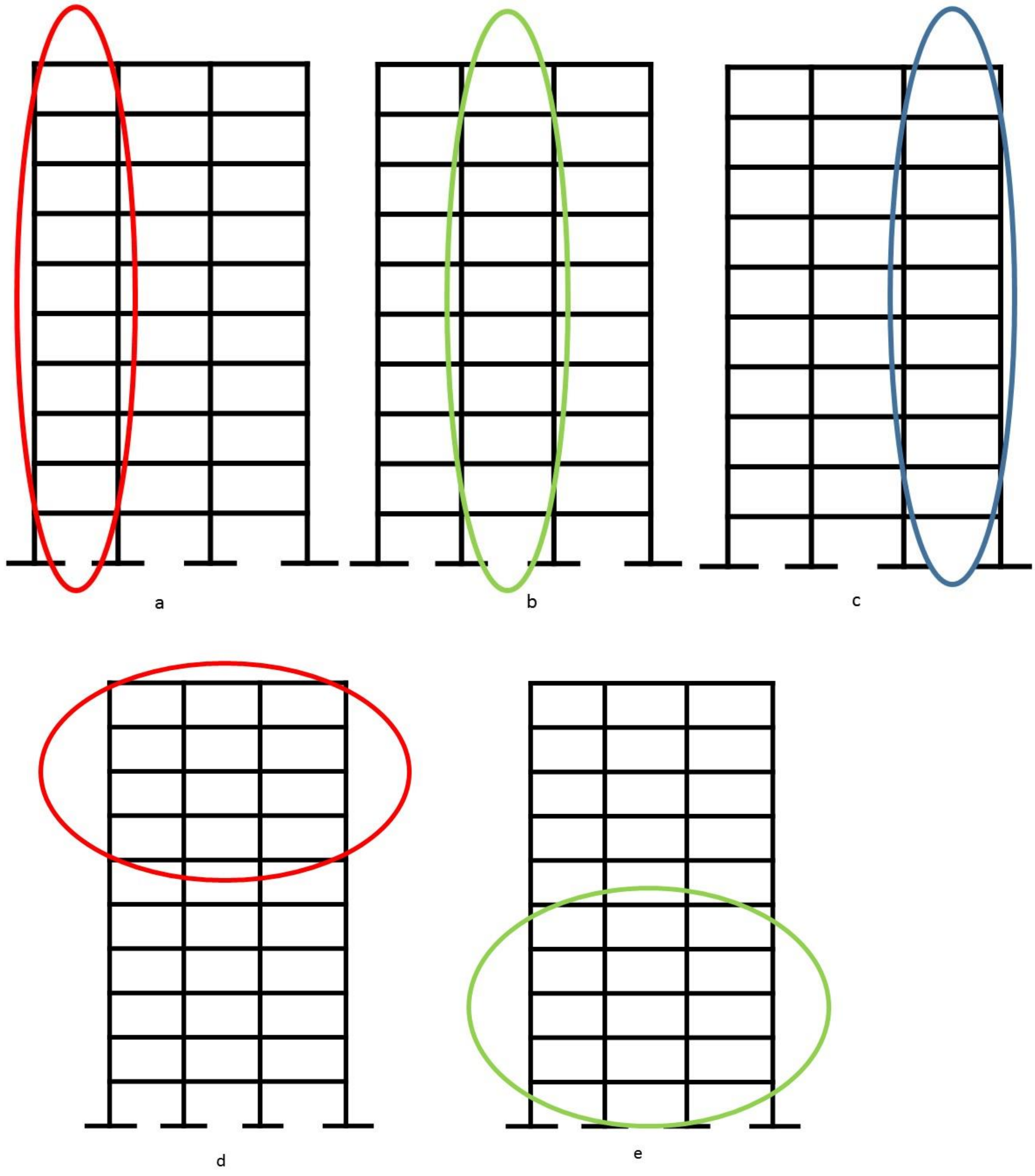


Figure 1 Damage scenarios for a 10 story building

mechanisms. The collapse load factor for each combined mechanism is expressed in terms of plastic moment capacities of beam and columns. Using genetic algorithm collapse load factor of the 10 story building frame for complete collapse mechanism is minimized with the constraint that no other mechanism can occur than the complete collapse mechanism. The results of the optimization provide values of the plastic moment capacity of all beams and columns. In this way, different combinations of plastic moment capacity of beams and columns are simulated for all the damage scenarios created. Each case will provide a collapse load factor. The one having the least value of the collapse load factor may be most vulnerable to an earthquake. However, the PGA value of the earthquake which will cause complete collapse of the structure is not known, nor the extent of the progress of further damage of the structure due to a certain level of PGA of earthquake is known.

In order to obtain this, a pushover analysis is performed for the building frames for each damage scenario generated as above. Plastic moment capacity of different members (M_i^p) and M_i^p vs θ_i^p curve for different cross-sections are provided as inputs. The capacity curve showing the variation of the base shear with top displacement of the frame is plotted in S_a(base shear divided by building weight) and S_d ($S_d = top\ displacement$) coordinates for each case of the damage scenario as shown in Figure 2**.**

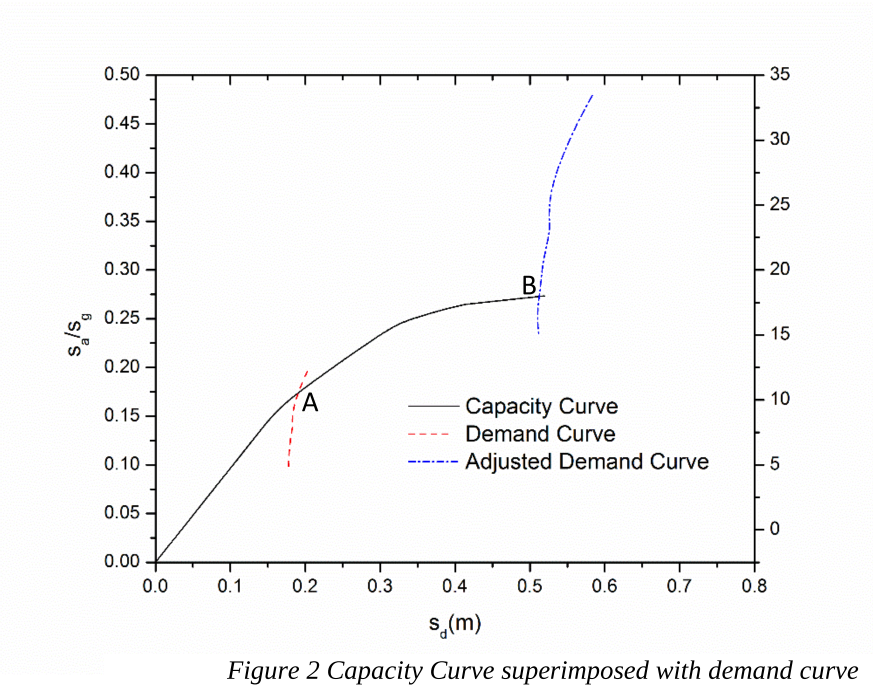


Figure 2 Capacity Curve superimposed with demand curve

The seismic demand of an earthquake denoted by its bi-spectrum (response spectrum plotted on $s_a - s_d$ axes) is plotted in the same figure 2. The peak ground acceleration (PGA) value of the demand curve is so adjusted that it intersects the capacity curve at the points (*B)* denoting the complete collapse of the frame as shown in Figure 2**.** Thus, for each damage scenario a PGA value is obtained. The one which gives the least value of PGA denotes the critical damage scenario. In other words, if a response spectrum consistent earthquake having the same PGA takes place, then the critical damage scenario of the frame described as above, will lead to complete collapse of the frame. For other damage scenarios, the frame will survive the earthquake with different degrees of damage. Thus, the critical damage scenario of the frame may be viewed as the one that will trigger progressive collapse of the frame to complete failure for the specific earthquake.

The damage states of the frame with other damages scenarios under the same earthquake can be assessed from the results of the pushover analysis. Note that the frame with critical damage scenario may not necessarily yield the least collapse load factor as obtained from plastic analysis.

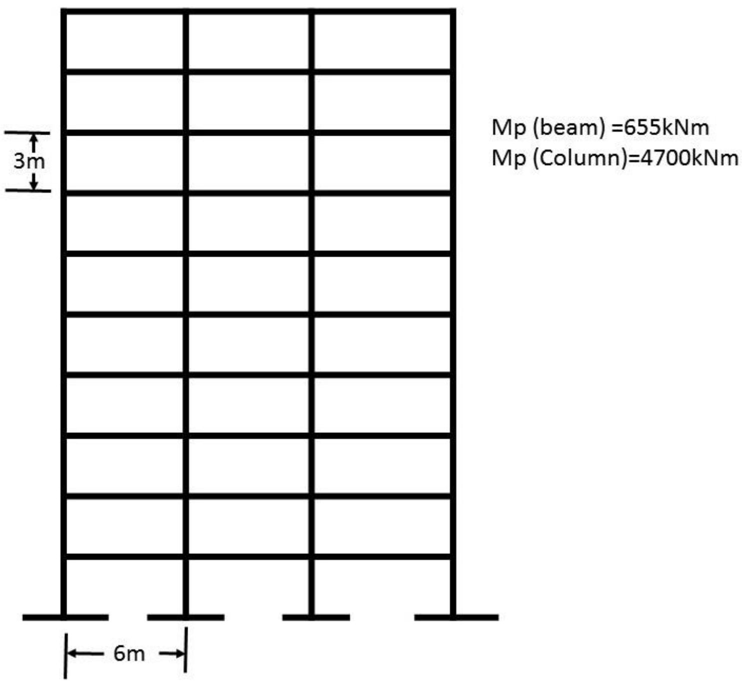


Figure 3 Building Frame

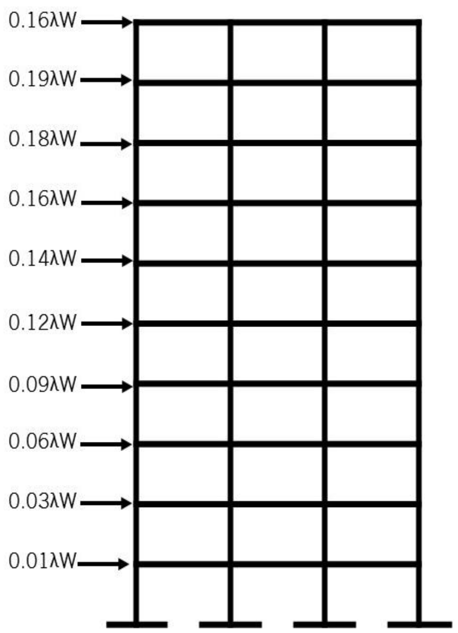


Figure 4 Distribution of lateral loads for plastic analysis of undamaged frame

3. Numerical Results and Discussion:

A 10 story 3 bay frame having a story height as 3m and bay of 6m is considered for the current study. The building frame is made up of steel sections, W21X68 as beams W33X291 as columns shown in the Figure 3. Dead loads of the roof and other floors are 87.74kN/m and 94.20kN/m respectively. Live load of the floors is 70.124kN/m and that on roof is 17.55kN.

Lateral loads applied on the structure for the plastic analysis is assumed to be proportional loading. The lateral loads bear a relationship with the shear force developed in the first mode of the structure. Loading condition for the plastic analysis is shown in Figure 4**,** where λ is collapse load factor, and W is the weight of the structure. A plastic analysis is carried out to determine the collapse load factor λ for the undamaged frame. The collapse mechanism which provides the least collapse load factor is the last but one combined sway mechanism. The corresponding collapse load factor is $\lambda = 0.2065$. This collapse load is utilized to find the base shear force for the collapse mechanism and is found to be 3675.4 kN

The same structure is analyzed by push over analysis using SAP 2000. The hinge locations for the collapse condition is as shown in Figure 5, which closely matches with those obtained by plastic analysis. The maximum base shear by push over analysis is 3769kN which is 2.5% higher than the base shear obtained by the plastic analysis.

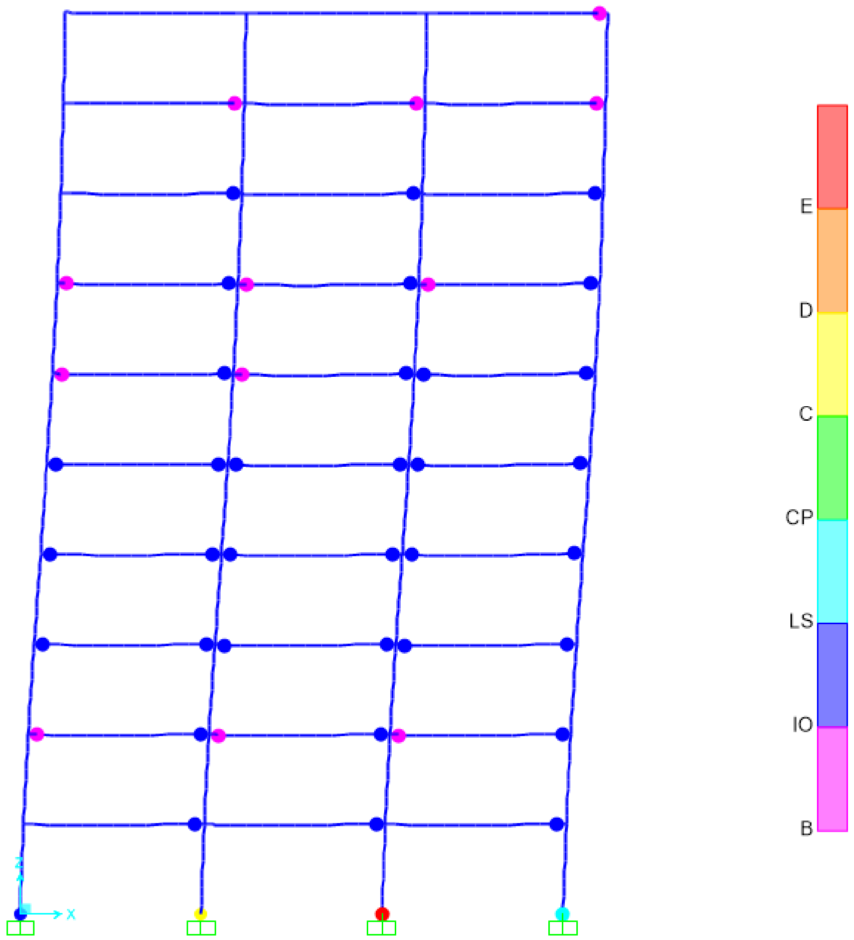


Figure 5 Hinge Location for the least value of λ for the undamaged frame

3.1 Damage Scenarios

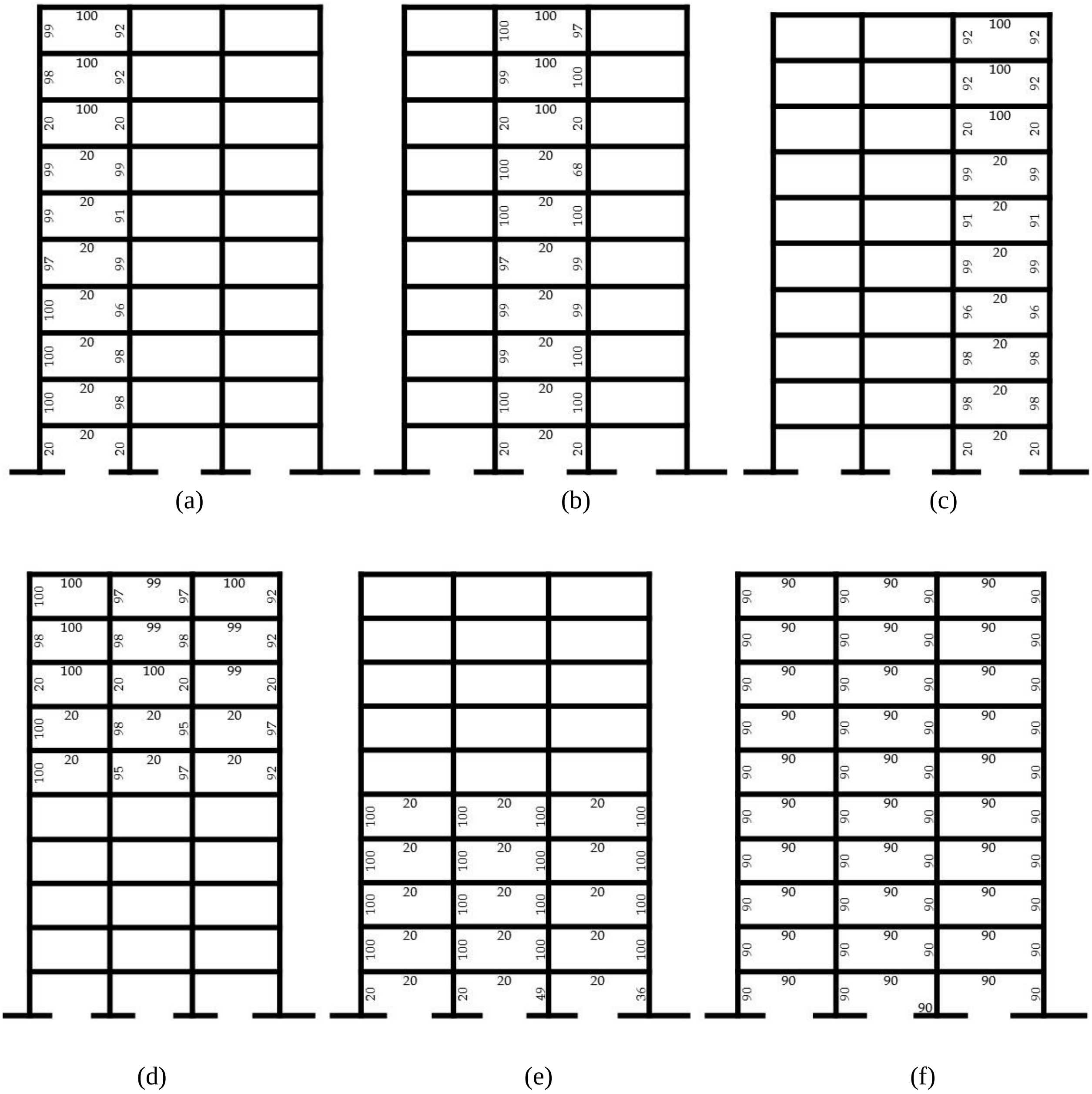
It is possible to create a number of damage scenarios keeping the total damage expresssed in terms of percentage reduction of total plastic moment capacity (sum of plastic moment capacities of beams and columns) of the frame to be the same. For the numerical example, 6 damage scenarios including the uniform damage are created. They are shown in figure 1(a-e). In case A, damages are localised in first bay; in case B, damages are localised in second bay; in case C, damages are loacted in the third bay; in case D, damages are localised in the upper storeys and in case E, damages are localised in the lower storeys. For the uniform damage scenario, plastic moment capacities of all members are uniformly reduced.

Reduced plastic moment capacities of damaged members for each damage scenario are obtained using GA with load factor λ as the objective function to be minimised fulfilling the constraints (i) reduction of total plastic moment capacity is equal to a specific value and (ii) full collapse mechanism is formed. Reduced plastic moment capacity of each damaged member is indicated in figure 6(a-f) for 10% total reduction of the plastic moment capacities of the member. In a similar way, percentage reductions of moment capacities of the members for 15% and 20% the total reduction are achieved.

It is seen from the table 1 that base shears obtained by plastic analysis differ for different type of damage.(A-E) & uniform damage. The base shear is found to be maximum for uniform damage Push over analysis is carried out for all damaged scenario. The base shears obtained by plastic analysis & pushover analysis compare well for all damage scenarios considered in the study. As it would be expected., base shear decrease as the total percentage damage is increased.

Table 1 Base shears obtained by plastic Analysis and Push over analysis

Damage scenarios	Base Shear (in kN)					
	10% Damage		15% Damage		20% Damage	
	Plastic analysis	Push over analysis	Plastic analysis	Push over analysis	Plastic analysis	Push over analysis
Case A	2102	2155	2070	2123	1866	1913
Case B	1962	2012	1925	1974	1861	1908
Case C	2102	2155	2070	2123	1866	1913
Case D	1820	1866	1715	1758	1605	1646
Case E	1757	1802	1744	1788	1704	1747
Uniform Damage	3308	3392	3123	3203	2940	3015



Figure; 6 Reduced moment carryng capacity of damaged member for; a) Case A; b) Case B; c) Case C; d) Case D; e) Case E; f) Uniform Damage

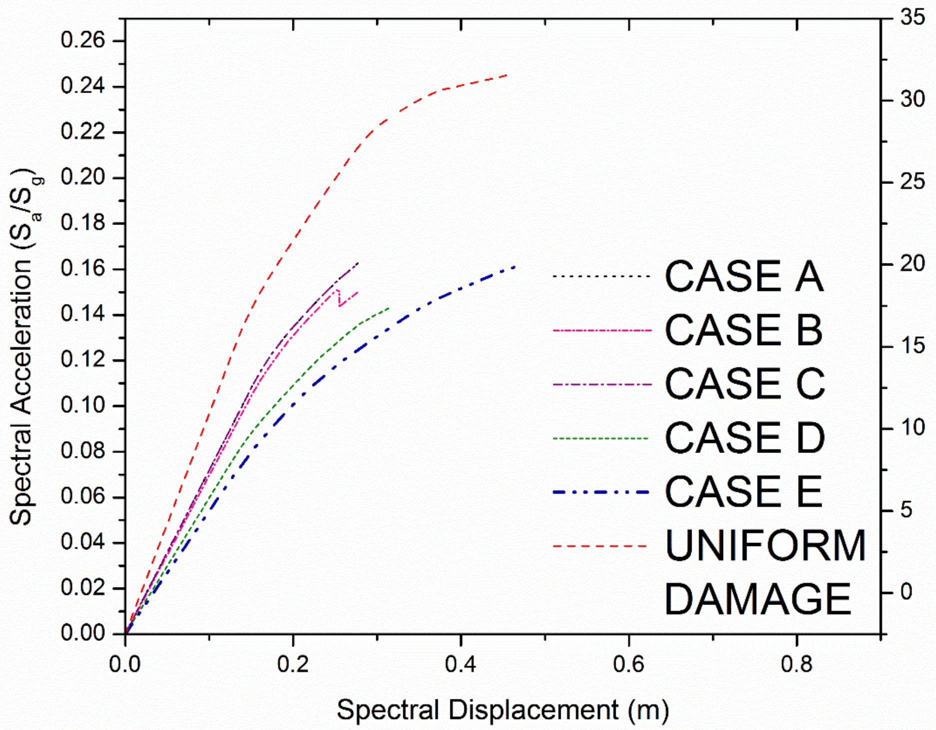


Figure 7 Capacity curve for different damage scenarios

The capacity curves for all cases of damage including the case of uniform damage are shown in figure 7. It is seen from the figure that compared to the case of uniform damage, all other damage scenarios provide lower capacity curves. The performance points obtained by superposing the seismic demand curves (using Acceleratio Displacement Response Spectrum(ADRS)) with capacity curves are pushed to coincide with the collapse points of different damage scenarios including the uniform damage by adjusting the PGA level. Table 2 shows the PGAs required to match the performance points with the collaps states of the capacity

Table 2 Adjusted PGAs for the performance point to match with collapse state for 10% total damage

Damage Scenarios	Performance Point		PGA(g)	No. of Plastic hinges at the PGA level of 0.493g
	Spectral Acceleration (g)	Spectral Displacement (m)		
Case A	0.165	0.284	0.545	46
Case B	0.144	0.255	0.493	58
Case C	0.165	0.284	0.545	46
Case D	0.143	0.312	0.545	40
Case E	0.156	0.425	0.70	48
Uniform Damage	0.24	0.380	0.855	36

curves for each scenario of damage. In the table the spectral acceleration and spectral displacement corresponding to the performance point for each case are also shown.

From the table, it is seen that damage scenario 'B' has the least PGA (PGA=0.493g). Therefore, if an earthquakre with PGA of 0.493g or more occurs, then a progressive collapse leading to complete failure of the frame having damage scenario 'B' will take place. For the PGA level of 0.493g, the frames with other damage states will be damaged by different degrees of damage but the frames will not collapse. Thus, from the point of progressive collapse due to an earthquake, the damage scenario 'B' is the most vulnerable. For other damage scenarios, the localized damage will progress to different states of damage i.e. there will be spread of damage in the structure during earthquake without complete collapse of the structure. The extent of damage is indicated by the total number of plastic hinges formed for different damage scenarios. When an earthquake of PGA=0.493g is encountered, the number of plastic hinges formed for each case is also shown in the table 2.

4. Conclusion

The possibility of Progressive collapse of damaged building frames under earthquake is examined with an assumption that certain existing localized damage in the building may trigger progressive collapse leading to either complete or partial collapse of the structure. In order to investigate it, a ten story building is artificially damaged to create different damage scenarios for a given total damage expressed in terms of a total percentage reduction of plastic moment carrying capacities of the beams and columns. This is achieved by using plastic analysis and genetic algorithm which satisfy two conditions namely, (i) total reduction in plastic moment capacities in each case is the same as the specified one, and (ii) full collapse mechanism is formed. Push over analysis of the frame is carried out for each damage scenario in order to obtain PGAs of the demand curve having the performance points coinciding with collapse point of the capacity curve. The damage scenario providing the least PGA value is most vulnerable to progressive collapse under the response spectrum compatible earthquake.

Following conclusion can be drawn from the numerical study
i) There exist certain localized damage states for a building frame which may trigger progressive collapse leading to complete failure under an earthquake.
ii) It is possible to identify these localized damage states using plastic analysis, genetic algorithm and push over analysis.
iii) For an earthquake with a certain PGA level, similarly constructed buildings may have different progressive damages depending upon their initial damage states.
iv) If the damage state of the building can be evaluated beforehand, vulnerability of the building to collapse under future earthquakes can be predicted using the methodology presented here.
v) The methodology may be usefully employed for retrofitting damaged building to withstand specific levels of earthquake intensity.

References

[1] A. Macilwraith, "Progressive collapse," Computers, p. 103205, 2006.

[2] C. Pearson and N. Delatte, "Ronan Point Apartment Tower Collapse and its Effect on Building Codes," J. Perform. Constr. Facil., vol. 19, no. 2, pp. 172–177, 2005.

[3] Department of Defense (DoD), "Design of Buildings To Resist Progressive Collapse," Unified Facil. Criteria 4-023-03, no. June, p. 245, 2009.

[4] U.S. General Services Administration (GSA), "Alternate Path Analysis & Design Guidelines for Progressive Collapse Resistance," U.S. Gen. Serv. Adm., 2013.

[5] G. Powell, "Progressive Collapse: Case Studies Using Nonlinear Analysis," Struct. Congr. 2005, vol. 1, no. 1, pp. 1689–1699, 2005.
[6] S. M. Marjanishvili, "Progressive Analysis Procedure for Progressive Collapse," J. Perform. Constr. Facil., vol. 18, no. 2, pp. 79–85, 2004.
[7] X. Guoqing and B. R. Ellingwood, "An energy-based partial pushdown analysis procedure for assessment of disproportionate collapse potential," J. Constr. Steel Res., vol. 67, no. 3, pp. 547–555, 2011.
[8] B. Ellingwood and E. Leyendecker, "Approaches for design against progressive collapse," J. Struct. Div., 1978.
[9] S. Marjanishvili and E. Agnew, "Comparison of various procedures for progressive collapse analysis," J. Perform. Constr. …, 2006.
[10] K. Menchel, T. J. Massart, D. Ph, Y. Rammer, and P. Bouillard, "Comparison and Study of Different Progressive Collapse Simulation Techniques for RC Structures," vol. 135, no. 6, pp. 685–697, 2009.
[11] L. Kwasniewski, "Nonlinear dynamic simulations of progressive collapse for a multistory building," Eng. Struct., vol. 32, no. 5, pp. 1223–1235, 2010.
[12] J. Kim, J. Park, and T. Lee, "Sensitivity analysis of steel buildings subjected to column loss," Eng. Struct., 2011.
[13] F. Fu, "Response of a multi-storey steel composite building with concentric bracing under consecutive column removal scenarios," J. Constr. Steel Res., 2012.
[14] M. Bandyopadhyay, A. K. Banik, and T. K. Datta, "Progressive Collapse of Three-Dimensional Semi-Rigid Jointed Steel Frames," pp. 1–23, 2008.
[15] J. Breen, ": Research Workshop on Progressive Collapse of Building Structures, Held at Joe C. Thompson Conference Center, the University of Texas at Austin," 1976.
[16] W. G. Corley, "Lessons Learned on Improving Resistance of Buildings to Terrorist Attacks," J. Perform. Constr. Facil., vol. 18, no. 2, pp. 68–78, May 2004.
[17] J. R. Hayes, S. C. Woodson, R. G. Pekelnicky, C. D. Poland, W. G. Corley, and M. Sozen, "Can strengthening for earthquake improve blast and progressive collapse resistance?," J. Struct. Eng., vol. 131, no. 8, pp. 1157–1177, 2005.