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Progressive Collapse Analysis of Steel Building with Bracing

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Abstract — *Progressive collapse is a disastrous structural event that occur because of human-made and natural hazards. Damage can be in form of loss of non-structural element, structural components and collapse of structural element leading to progressive failure of part or whole building. The failure of a member in the primary load resisting system leads to redistribution of forces to the adjoining members and if redistributed load exceeds member capacity it fails. This process continues in the structure and eventually the building collapses. The present work investigates the effect of concentric bracing on the progressive collapse potential of steel building. Linear static analysis of building model with and without bracing are carried out using the alternate path method recommended by the General Service Administration (GSA guideline) using software SAP2000. The building model would be of 8 storey steel building which includes X type bracing system with different arrangement. The X types of bracing system is evaluated with two different arrangement of bracing to get maximum resistance from Progressive Collapse. The demand capacity ratio of building is evaluated by GSA guidelines and is compared with different models which include building with and without bracing. Effect of removal of columns at different locations which include forces and moments are studied and compared. The study shows that moment frame with concentric bracing exhibited desirable resistance against progressive collapse.*

Keywords- *Progressive collapse analysis, steel structure, concentric bracing, alternate path method, linear static analysis*

I. INTRODUCTION

During the recent years, a lot of attention has been paid to probable progressive collapse among the building owners in every parts of the world. This is because of the fact that progressive collapse is a potentially destructive event for huge buildings leading to serious number of casualties and injuries for their residing people and also may lead to significant damage to properties.The progressive collapse of structures is commenced when the primary component(s), usually columns, is eliminated. When a column is suddenly removed as a result of a vehicle collision, explosion, terrorist attacks, earthquake and other natural or artificial hazards, gravity loads (Dead Load and Live Load) gets transmitted to adjoining columns in the structure. If these primary elements are not appropriately designed to bear and redistribute the overloading, that portion of the structure or the whole of the structure may collapse. Because of that, a portion of the building may get damaged and fall down because of the larger and superior damage to the building than the preliminary impact.

Although progressive collapse is generally a very rare phenomena in developed countries, but its effect on buildings is very dangerous and costly. Without significant consideration of adequate continuity, ductility and redundancy, the progressive collapse cannot be prevented. Some past example of progressive collapse are Ronan point apartment tower in East London blast on eighteenth floor which destructed load-bearing precast concrete plates adjoining the junction of the building. There was support lost at the eighteen floor due to which the above structure to collapse. The impact of these collapsing resulted in to destruction of whole structure till ground. The other example of progress of consecutive damage during the progressive collapse, which occurred in Alfred P Murrah building in Oklahoma City, in 1995 resulted in 168 fatalities [11]. Due to this failure, several exploratory documents on the destruction and progression of collapse were transcribed. After the collapse of World Trade Centre due to terrorist attacks, many government organization and local agencies have worked on developing guidelines for designing structure to resist progressive collapse. The General Service Administration (GSA) guideline and Unified Facilities Criteria (UFC) by Department of Defence guideline developed by USA are used because they give analysis procedure and design requirements of structures to survive the collapse. According to GSA guidelines, progressive collapse is a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Once a column is failed the building weight transfers to neighbouring members in the structure. If these members are not properly designed to resist and redistribute the additional load that part of the structure fails. So to redistribute additional load the bracing are provided in this study.

Marjanishvili (2004) studied the progressive collapse of steel building by four analysis method. The simplest analysis methodology includes static linear elastic procedures, and the most exhaustive procedure is nonlinear time history analysis [2]. Agnew and Marjanishvili (2006) the linear static analysis procedure is performed using an amplified (by a factor of 2) combination of service loads, such as dead and live, applied statically. The dynamic amplification factor of 2 used is a good estimate for static analysis procedures since linear static and linear dynamic analysis procedures yield approximately the same maximum deflections [3].

Bilow and Kamara (2004) studied parameters of axial load, flexure and shear reinforcement for different seismic categories [4]. Joshi, Patel and Tank (2010) concluded that, if structures designed and detailed with a good level of continuity, redundancy and ductility can develop alternative load paths following the loss of an individual member and prevent progressive collapse [5]. Song, Sezen and Giriunas (2010) Progressive collapse performance of two existing buildings was investigated through both experimental testing and computational analysis [6].

II. GUIDELINES AND METHEDOLOGY

The US General Service Administration (GSA) commonly recommend the Alternate Path method especially for buildings with maximum 10 stories high, based on a feasible framework [10]. In this method, the probability of progressive collapse is reduced by providing redundancy in the structure. The structure is designed such that if any one member fails, alternate load paths are available for the load that was in that component and a general collapse does not occur. This approach has the benefit of simplicity and directness. In its most common application, design for redundancy requires that a building structure be able to tolerate loss of any one key element without collapse. There are four methods for analysis of progressive collapse in buildings: 1) Linear static method (LSM). 2) Non-Linear static method (NLSM). 3) Linear Dynamic method (LDM). 4) Non-Linear Dynamic method (NLDM) [10]. For current study linear static method is used for progressive collapse analysis.

2.1 Linear Static Analysis loading

According to GSA guidelines, for static analysis procedures the below mentioned vertical load should be used for these case studies [10]:

Load = 2(1.2DL + 0.25LL)

Where DL= Dead load, LL = Live load and 2 is dynamic amplification factor

2.2 Calculation of Demand Capacity Ratio (DCR) and Acceptance criteria

In order to determine the susceptibility of the building to Progressive Collapse, Demand Capacity Ratio should be calculated based on the following equation:

$DCR=Q_{ud}/Q_{ce}$

Where,
Q_{ud}= Acting force (Demand) determined or computed in element or connection/joint.
Q_{ce} = Probable ultimate capacity (Capacity) of the component and/or connection/joint.

Referring to DCR criteria defined through linear static approach, different elements in the structures and connections with quantities value less than 1.5 or 2 are considered not collapsed as follows:

$DCR < 2.0$: for typical structural configuration
$DCR < 1.5$: for atypical structural configuration

The model which is used have typical structural configuration so the $DCR < 2$.Since the loading pattern used in this study for analysis is based on just gravity (amplified dead and live load), computation of DCR values for braces are neglected, DCR has been calculated only for beams and columns. In this study, Demand Capacity Ratio should be computed for moment, axial force and shear[10].

2.3 Procedure of Linear Static Analysis

The procedure for linear static analysis is shown in the flow chart below:

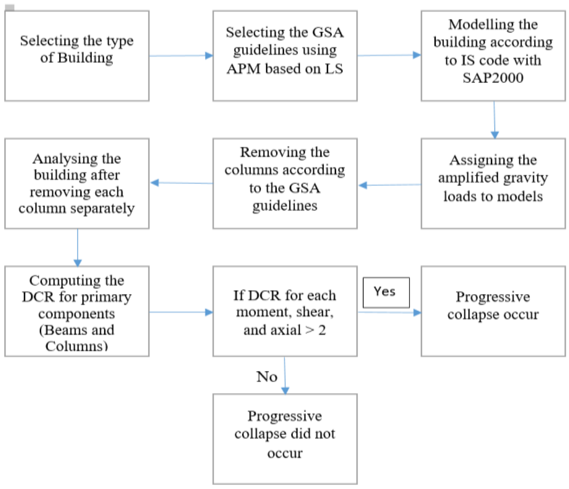


Figure -1: Flow chart for procedure of linear static analysis.

III. BUILDING CONFIGURATION AND MODELS

One important and effective factor in the strength of structures against progressive collapse is the type of lateral load resisting system. By changing the load path on the effect of removing a critical member such as column, the force of the removed member, as a result of this event must be transmitted to other parts of the structure by neighboring members. In this study three models of 8 story steel building with and without bracing with two types of bracing arrangement are used, the building data is given below:

3.1 Model Data

- Storey : G+7 Storey building
- Usage : Residential Structure
- Location : zone IV
- Structural System : Moment Resisting frame
- Area : 37.5m X 24m
- Total Height of Building : 17.5m (G+4) & 28m (G+7)
- Typical Bay width : 7.5m width in x-direction (5 bays)
  8.0m width in y-direction (3 bays)
- Typical storey height : 3.5m
- Thickness of Slab : 90mm
- Beam Size : ISMB-500
- Secondary Beam Size : ISMB-450
- Column Size : ISHB-450-I With Plates of (400mm*32mm)on both side of flanges
- Bracing : ISNB-300H

3.2 Material Properties

The material properties used in the models are as follows:

- Modulus of Elasticity: E = 210000 N/mm^2
- Poisson's Ratio: u = 0.3
- Weight per Unit Volume: 7.697E-05 N/mm^3
- Mass per Unit Volume: 7.849E-09 N/mm^3

- Minimum Yield Stress: 250 N/mm^2

3.3 Loading Data

The loads which are considered for this analysis are Dead loads, Live loads & Earthquake loads.

- The dead load include the self-weight of sections and slab.
- Floor finish = 1KN/m^2
- Terrace water proofing = 1KN/m^2
- Wall load on periphery beams = 20.5 KN/m

2) Live load

- Live load on all floor except roof = 2.5 KN/m^2

3) Earthquake load

- Zone = IV
- Importance factor = 1
- Response reduction factor =5
- Type of soil = Medium

3.4 Location of Column removal

Three representative column removal locations were considered in this analysis example as shown in figure below:

1. Removal 1 – Long side column condition (D-1).
2. Removal 2 – Short side column condition (A-3).
3. Removal 3 – Corner column condition (A-1).

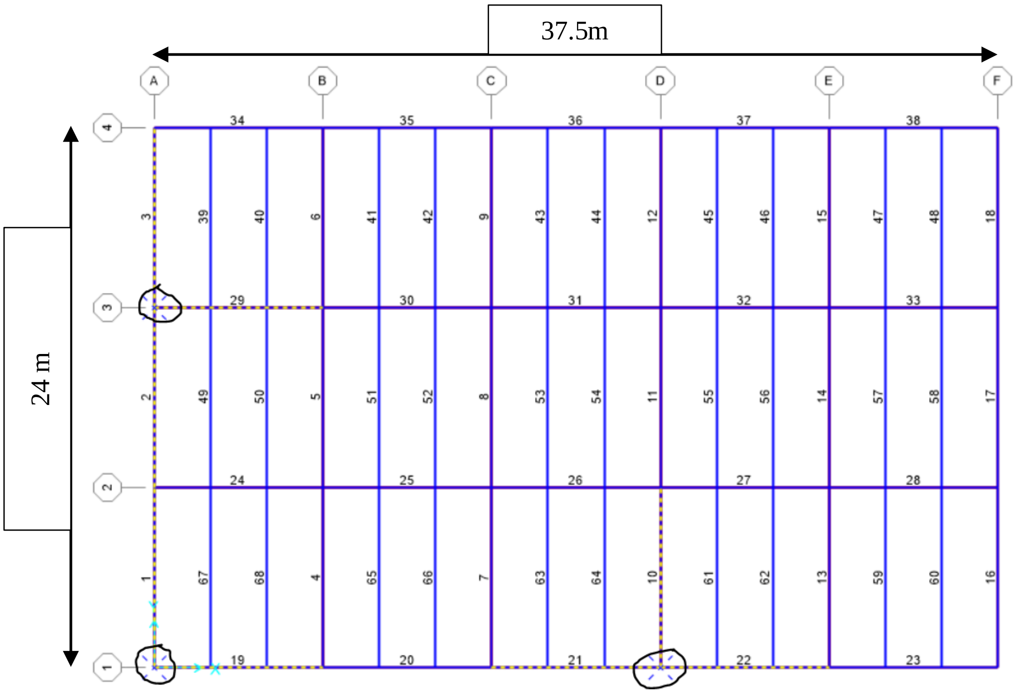


Figure -2: Location of column removal

3.5 Three Dimensional Model

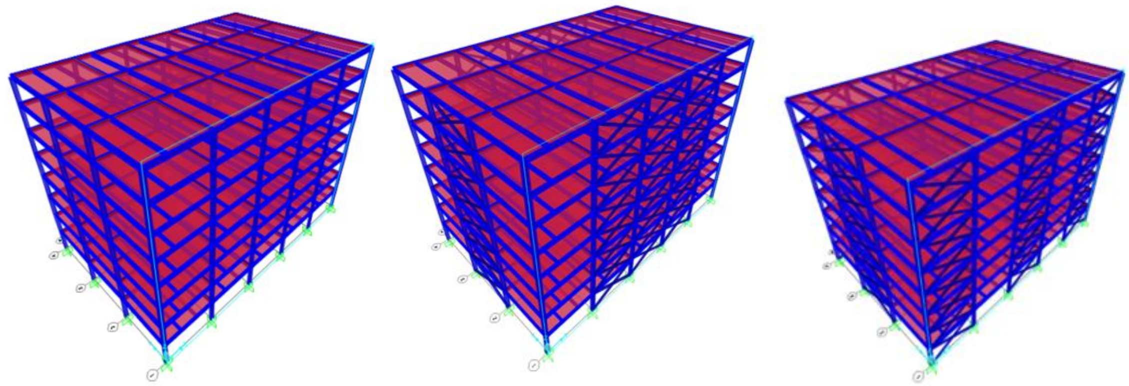


Figure -3: 3D models of 1) Building without bracing. 2) Building with X bracing with neighbor arrangement. 3) Building with X bracing with alternate arrangement.

The above figure shows the arrangement of the bracing for the analysis. This model would also be analysed under three column removal scenario. The bracing section provided are Indian standard hollow circular steel section ISNB300H. Design of bracing is done by IS 800-2007. The arrangement of bracing is changed only in the longitudinal direction (x-direction).

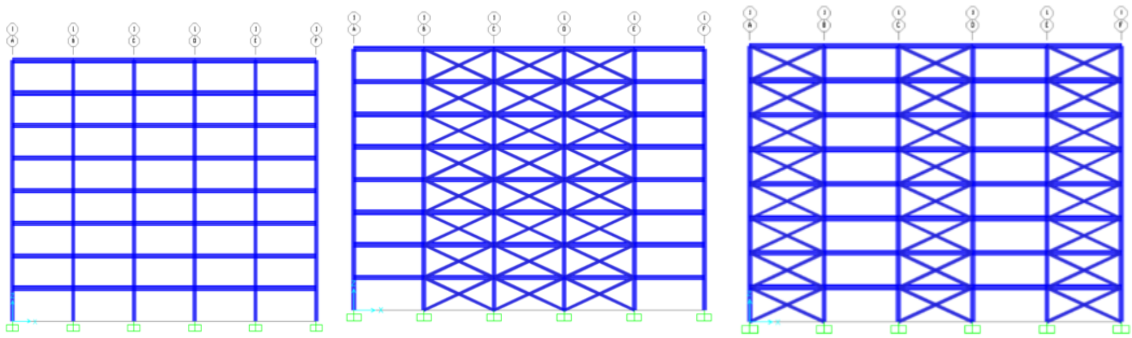


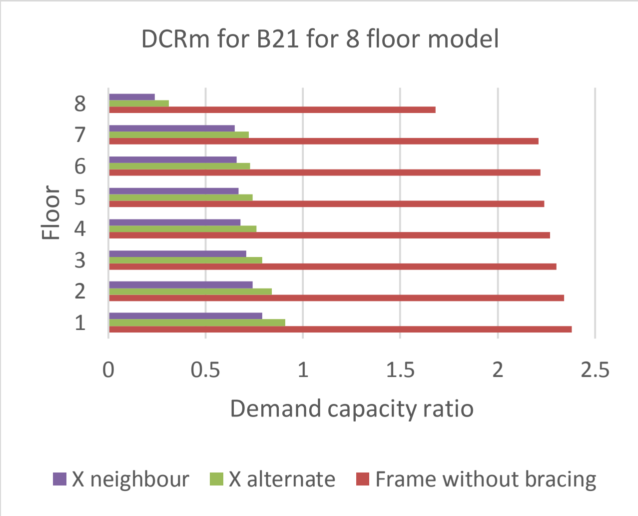
Figure -4: 2D models of 1) Building without bracing. 2) Building with X bracing with neighbor arrangement. 3) Building with X bracing with alternate arrangement.

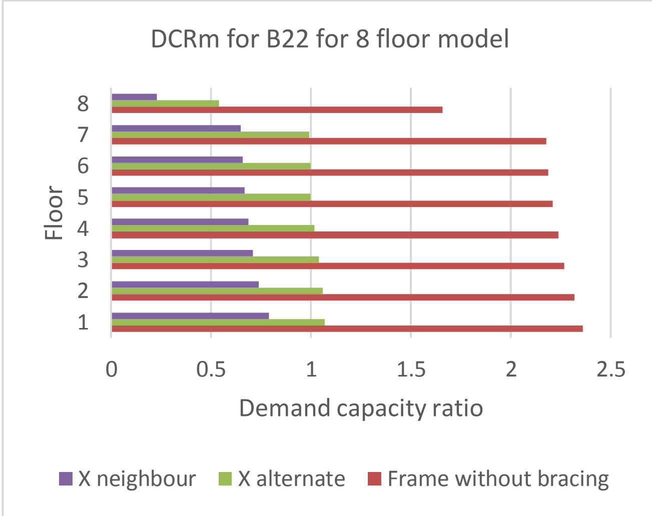
IV. RESULTS AND DISCUSSION

The linear static analysis is carried out for all the models including all column removal case. The value of Demand Capacity Ratio (DCR) for moment, shear and axial force are obtained for all models and then the values are compared. The comparison of DCR_m is represented in graphically form below:

4.1 Results of Case 1 removal.

The long side middle column “1D” is removed and the values of the DCR that is demand capacity ratio is computed. The results of the effective members are shown in the form of chart below:





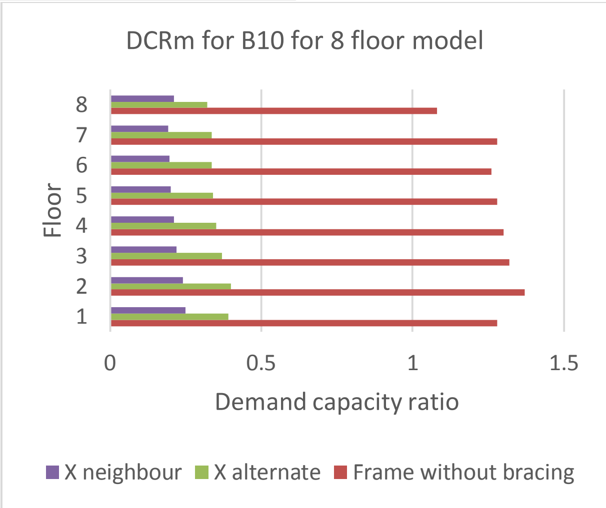
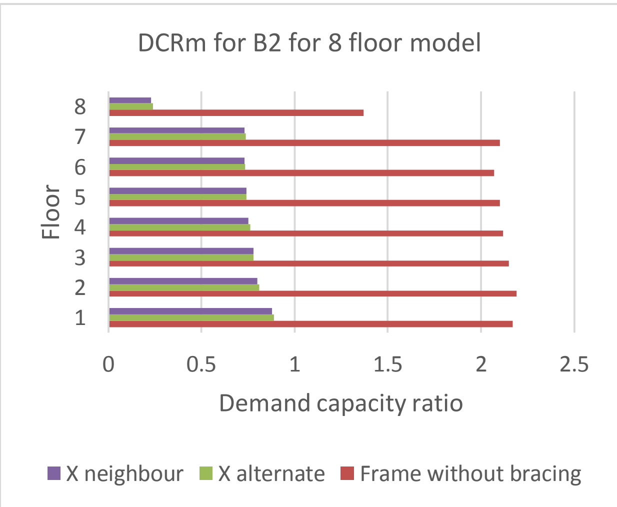
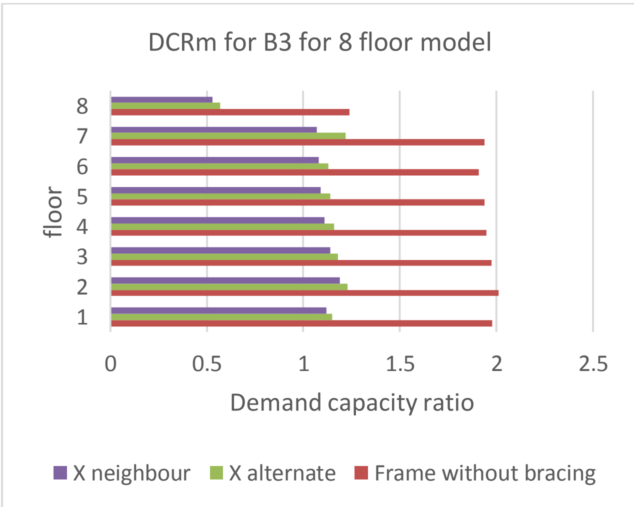


Chart-1: Comparison of DCR_m for affected beam by column removal case 1

4.2 Results of Case 2 removal





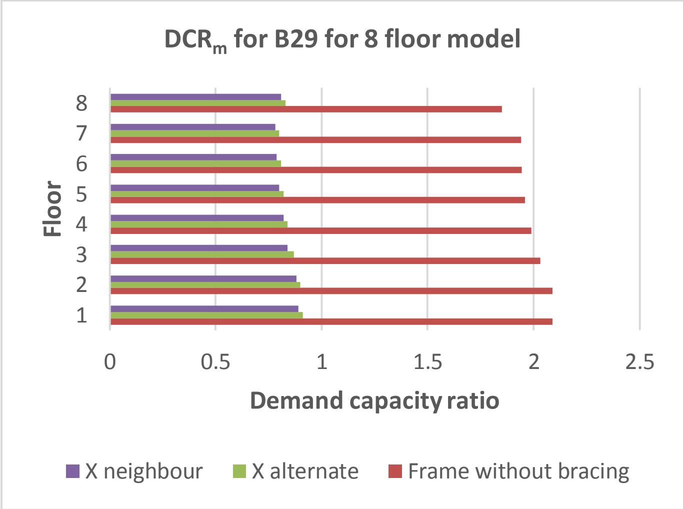


Chart-2: Comparison of DCR$_m$ for affected beam by column removal case 2

4.3 Results of Case 3 removal

The below charts shows the DCR$_m$ for the column removal case-3. The column removed is the corner column

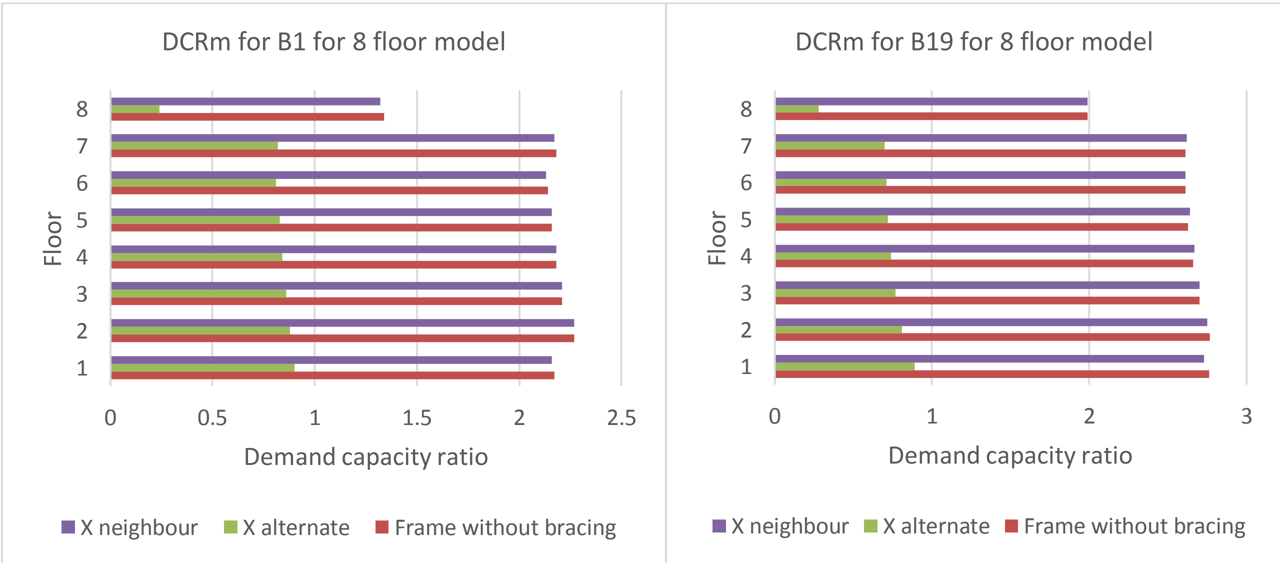


Chart-3: Comparison of DCR$_m$ for affected beam by column removal case 3

The above charts shows the demand capacity ratio of moment for affected beams. From the charts we can observe that the building without bracing considered for this research is highly prone to progressive collapse when the column is removed from the ground floor. But due to bracing the potential of progressive collapse is drastically reduced making the structure less prone to progress collapse. The values of DCR$_m$, DCR$_{shear}$ and DCR$_{axial}$ are given in the form of table below:

Table-1: Summary of DCR_m for Beams Adjacent to Eliminated Columns

	DCR_m	LONG SIDE COLUMN REMOVAL			SHORT SIDE COLUMN REMOVAL			CORNER COLUMN REMOVAL	
	Floor	**B21**	**B22**	**B10**	**B2**	**B3**	**B29**	**B1**	**B19**
Without Bracing	1	2.38	2.36	1.28	2.17	1.979	2.088	2.17	2.763
	2	2.34	2.32	1.37	2.19	2.01	2.089	2.27	2.765
	3	2.3	2.27	1.32	2.15	1.975	2.033	2.21	2.7
	4	2.27	2.24	1.3	2.12	1.95	1.99	2.18	2.66
	5	2.24	2.21	1.28	2.1	1.94	1.96	2.16	2.63
	6	2.22	2.19	1.26	2.07	1.91	1.944	2.14	2.611
	7	2.21	2.18	1.28	2.1	1.94	1.941	2.18	2.613
	8	1.68	1.66	1.08	1.37	1.24	1.85	1.34	1.99
X Bracing Alternate	1	0.91	1.07	0.39	0.89	1.15	0.91	0.9	0.89
	2	0.84	1.06	0.4	0.81	1.23	0.9	0.88	0.81
	3	0.79	1.04	0.37	0.78	1.18	0.87	0.86	0.77
	4	0.76	1.02	0.35	0.76	1.16	0.84	0.84	0.74
	5	0.74	1	0.34	0.74	1.14	0.82	0.83	0.72
	6	0.729	0.998	0.336	0.735	1.129	0.81	0.81	0.71
	7	0.721	0.994	0.335	0.736	1.22	0.8	0.82	0.7
	8	0.31	0.54	0.32	0.24	0.57	0.83	0.24	0.28
X Bracing Neighbour	1	0.79	0.79	0.25	0.88	1.12	0.89	2.16	2.73
	2	0.74	0.74	0.24	0.8	1.19	0.88	2.27	2.75
	3	0.71	0.71	0.22	0.78	1.14	0.84	2.21	2.7
	4	0.68	0.69	0.21	0.75	1.11	0.82	2.18	2.67
	5	0.67	0.67	0.2	0.74	1.09	0.8	2.16	2.64
	6	0.66	0.66	0.196	0.73	1.079	0.788	2.13	2.61
	7	0.65	0.65	0.192	0.73	1.07	0.781	2.17	2.62
	8	0.24	0.23	0.21	0.23	0.53	0.81	1.32	1.99

The above table gives us the summary about the demand capacity ratio for moments. The values clearly states that DCR ratio without bracing is greater than 2 so the structure is prone to progressive collapse. But the DCR ratio decrease when the bracing are provided. The most efficient bracing is the alternate arrangement of the bracing which reduce the overall demand capacity ratio. The DCR for shear and axial are given in the table below:

Table-2: Summary of DCR_{shear} for Beams Adjacent to Eliminated Columns

	DCR_{shear}	LONG SIDE COLUMN REMOVAL			SHORT SIDE COLUMN REMOVAL			CORNER COLUMN REMOVAL	
	Floor	B21	B22	B10	B2	B3	B29	B1	B19
Without Bracing	1	0.660	0.660	0.240	0.594	0.569	0.465	0.574	0.724
	2	0.650	0.650	0.270	0.596	0.570	0.472	0.603	0.732
	3	0.649	0.640	0.265	0.588	0.564	0.461	0.590	0.720
	4	0.642	0.636	0.261	0.583	0.560	0.454	0.586	0.713
	5	0.637	0.631	0.258	0.579	0.557	0.449	0.582	0.707
	6	0.632	0.627	0.254	0.575	0.553	0.444	0.577	0.702
	7	0.631	0.626	0.259	0.579	0.556	0.444	0.589	0.703
	8	0.380	0.375	0.220	0.280	0.260	0.447	0.253	0.426
X Bracing Alternate	1	0.380	0.413	0.102	0.362	0.410	0.251	0.365	0.380
	2	0.369	0.411	0.105	0.345	0.422	0.250	0.358	0.365
	3	0.361	0.406	0.100	0.341	0.414	0.243	0.355	0.358
	4	0.355	0.403	0.097	0.337	0.410	0.239	0.351	0.353
	5	0.351	0.400	0.095	0.334	0.406	0.235	0.349	0.349
	6	0.348	0.398	0.093	0.332	0.403	0.232	0.347	0.346
	7	0.346	0.397	0.093	0.331	0.402	0.231	0.349	0.345
	8	0.110	0.150	0.100	0.075	0.129	0.257	0.067	0.106
X Bracing Neighbour	1	0.359	0.359	0.079	0.359	0.404	0.247	0.570	0.720
	2	0.350	0.351	0.077	0.343	0.414	0.245	0.604	0.730
	3	0.344	0.345	0.074	0.339	0.406	0.239	0.590	0.720
	4	0.339	0.340	0.071	0.335	0.401	0.234	0.585	0.710
	5	0.336	0.337	0.070	0.332	0.397	0.231	0.581	0.708
	6	0.334	0.335	0.068	0.330	0.394	0.228	0.576	0.703
	7	0.330	0.330	0.067	0.330	0.393	0.226	0.586	0.704
	8	0.098	0.098	0.080	0.070	0.120	0.253	0.251	0.427

Table-3: Summary of DCR_{axial} for columns Adjacent to Eliminated Columns

	DCR_{axial}	LONG SIDE COLUMN REMOVAL			SHORT SIDE COLUMN REMOVAL			CORNER COLUMN REMOVAL	
	Floor	1C	1E	2D	2A	4A	3B	1B	2A
Without Bracing	1	0.908	0.910	0.807	0.913	0.628	0.899	0.978	0.928
	2	0.786	0.787	0.707	0.791	0.531	0.785	0.849	0.807
	3	0.665	0.666	0.604	0.669	0.434	0.670	0.718	0.682
	4	0.546	0.546	0.503	0.548	0.337	0.558	0.589	0.559
	5	0.427	0.427	0.403	0.428	0.241	0.446	0.461	0.436
	6	0.309	0.309	0.303	0.309	0.145	0.336	0.334	0.315
	7	0.192	0.192	0.204	0.190	0.048	0.226	0.208	0.193
	8	0.075	0.075	0.105	0.072	0.725	0.117	0.081	0.071

	DCR_{axial}	LONG SIDE COLUMN REMOVAL			SHORT SIDE COLUMN REMOVAL			CORNER COLUMN REMOVAL	
X Bracing Alternate	**1**	1.118	0.545	0.667	1.095	0.465	0.712	1.044	0.670
	2	0.987	0.473	0.584	0.987	0.400	0.623	1.043	0.582
	3	0.801	0.407	0.501	0.813	0.332	0.534	0.920	0.496
	4	0.634	0.338	0.418	0.653	0.261	0.445	0.746	0.408
	5	0.481	0.267	0.336	0.501	0.187	0.357	0.590	0.320
	6	0.338	0.194	0.254	0.355	0.111	0.270	0.447	0.230
	7	0.201	0.119	0.172	0.214	0.033	0.182	0.314	0.139
	8	0.068	0.043	0.090	0.073	0.529	0.096	0.187	0.047
X Bracing Neighbour	**1**	0.866	0.926	0.648	1.101	0.504	0.706	0.927	0.932
	2	0.750	0.806	0.567	0.993	0.424	0.617	0.799	0.806
	3	0.607	0.656	0.486	0.820	0.345	0.529	0.672	0.678
	4	0.480	0.520	0.406	0.659	0.266	0.441	0.549	0.553
	5	0.364	0.395	0.327	0.506	0.188	0.354	0.429	0.430
	6	0.255	0.277	0.247	0.359	0.110	0.267	0.310	0.309
	7	0.152	0.165	0.167	0.152	0.165	0.167	0.194	0.190
	8	0.052	0.055	0.088	0.052	0.055	0.088	0.077	0.070

IV. CONCLUSION

In structure with concentrically lateral seismic bracing system, by removing the critical elements determined by GSA progressive collapse guideline and by performing progressive collapse analysis by alternate path analysis on the steel building model the following results have been obtained:

(1)The most critical column removal case is the column removed from the corner compared to the long side removal and short side removal. DCR values for moment, shear and axial decrease as the height of the building increase so the progressive collapse potential also decrease as the height increase.

(2) By providing the bracing the progressive collapse potential of the steel building model is reduced by approximately by 65% because the bracing provide more suitable alternate paths and the ability of better distribution of loads by increasing in the redundancy of the structure.

(3) Among the type of arrangement of bracing, arrangement of alternate bracing supported more column removal compared to the neighbor arrangement against the progressive collapse and has performed better.

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