Progressive collapse of regular and irregular reinforced concrete moment frame

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Abstract. A technique to evaluate the potential progressive collapse of reinforced concrete structure was conducted in this study. The analysis involved the removal of several columns on critical location of the building according to General Services Administration (GSA) 2013 provision. In each analysis, the demand-capacity ratios (DCRs) of structural elements were examined and compared to the defined acceptance criteria. To avoid structural building collapse progressively, DCR ratio of regular and irregular buildings should be less than 2 and 1.5, respectively. The result showed that the structure did not collapse with the removal single column only. Further to this finding, several columns need to be removed so that it collapsed progressively. In the case of regular structure, progressive collapse occurred after removing five columns on the side of the regular structure, with the maximum DCR of 4.66. In the case of irregular structure, progressive collapse occurred after removing four columns on the horizontal side in the middle of structure with the maximum DCR of 3.44.

1 Introduction

The collapse of the World Trade Center (WTC) in New York on September, 11 2001 was extraordinary because the structure collapsed with progressive collapse. The impact of aircraft crashes that trigger fires in some buildings cause local failure of structures in the area of the plane crash. Failure of the structure gives a gradually vertical load to the floor below and leads to the progressive collapse in the building. Based on the type of collapse occurring, progressive failure is divided into pancake-type, zipper-type, domino-type, section-type, instability-type and mixed-type collapse [1]. The WTC building collapsed with pancake type, which affords little opportunity to rescue because the collapse occurs very quickly. It is in contrast to the domino type that occurs gradually that offers a more significant opportunity to save people.

A multi-story building has the potential to collapse due to gravity load and the lateral load of the earthquake, which may even lead to the progressive collapse of the building. Therefore, research needs to evaluate the potential progressive failure of regular and irregular reinforced concrete structure, by analyzing the structural elements that were first

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destroyed due to the addition of gravity load and a lateral load of the earthquake by removing one or more elements of the building structure.

The primary purpose of this study is to evaluate the potential progressive collapse of the reinforced concrete structure. The benefits of this study are as follows: 1) to provide information for building planning to predict the progressive collapse characteristics of regular and irregular building structural components; 2) to provide information on collapse type of buildings in case of demolition of the regular and irregular building structure, and 3) to contribute as a reference to study about progressive collapse characteristics of regular and irregular concrete building structures.

2 Regular and irregular building structure

Building structures are classified as regular and irregular buildings [2]. The classification is based on the horizontal and vertical configuration of the building structure. Specifically, in this study, it only limits the problem of structural irregularities in the horizontal direction, as shown in Table 1.

Table 1. Horizontal irregularities in building structure [2].

No	Type and explanation of irregularity
1a	Torque irregularities are defined to exist if the maximum level inter-floor drift, the calculated torque, including the unexpected, at a transverse end of the structure against the axis is more than 1.2 times the mean inter-floor deviation at both ends of the structure.
1b	Excessive torque irregularities are defined to exist if the maximum level inter-floor drift, the calculated torque, including the unexpected, at a transverse end of the structure against the axis is more than 1.4 times the mean inter-floor deviation at both ends of the structure.
2	The inner angular irregularity is defined if both the projected structural planes of the inner corners are greater than 15 percent of the dimensions of the structural plan in a given direction.
3	The irregularities of diaphragmatic discontinuities are defined to exist when there is a diaphragm with discontinuity or sudden variation in stiffness, including those having cut or open areas greater than 50 percent of the gross diaphragm area surrounding it, or an effective diaphragm stiffening change of more than 50 percent from one level to the next.
4	The irregularity of transverse shift to the plane is defined to exist if there is discontinuity in the lateral force resistance path, such as the transverse shift to the vertical element plane.
5	Nonparallel system irregularities are defined to exist if the vertical lateral force retaining elements are not parallel or symmetric to the major orthogonal axes

3 Progressive collapse

The General Services Administration (GSA) provides guidelines for progressive collapse [3]. This guideline aims to reduce the potential for progressive failure in government offices, assess the potential for progressive failure of existing government office buildings, and assist in the development process of upgrading facilities. The scenario in this guide is to delete the columns on the first floor. Recommended locations in column deletion are as follows: 1) Removal of the column in the middle or near the middle of the short side of the structure; 2) Removal of the column in the middle or near the center of the long side of the structure; 3) Removal of the corner column; and 4) Removal of interior columns.

The approach is based on Demand Capacity Ratio (DCR) for structural elements and compares DCR values with threshold values to identify structural collapse.

DCR is calculated according to the following formula:

$$DCR = Q_{ud}/Q_{ce} \quad (1)$$

where Q_{ud} is the force obtained in the component (moment, axial force, shear and conjugation of force) obtained from linear elastic analysis, and Q_{ce} is the approximate strength of the component (moment, axial force, shear and conjunction of force combined). The DCR values allowed for structural elements are as follows: 1) $DCR < 2.0$ for regular structural configuration, 2) $DCR < 1.5$ for irregular structural configuration.

Based on the GSA guide, in linear or nonlinear static analysis, procedures use $2(DL+0.25LL)$ load combination, whereas, in linear or nonlinear dynamic analysis, procedures use $(DL+0.25LL)$ load combination where DL is the dead load and LL is the live load [3]. The critical load combination for buildings is derived from comparison of the GSA method and SNI 1726-2012. Load combination could be seen in Table 2.

Table 2. Load combination [2].

No	Load Combination	Remarks
1	1.4 DL	Combination 1
2	1.2 DL + 1.6 LL	Combination 2
3	1.2 DL + LL + Ex + 0.3 Ey	Combination 3-1
4	1.2 DL + LL + Ex - 0.3 Ey	Combination 3-2
5	1.2 DL + LL - Ex + 0.3 Ey	Combination 3-3
6	1.2 DL + LL - Ex -0.3 Ey	Combination 3-4
7	1.2 DL + LL + 0.3 Ex + Ey	Combination 3-5
8	1.2 DL + LL + 0.3 Ex - Ey	Combination 3-6
9	1.2 DL + LL - 0.3 Ex + Ey	Combination 3-7
10	1.2 DL + LL - 0.3 Ex - Ey	Combination 3-8
11	0.9 DL + Ex + 0.3 Ey	Combination 4-1
12	0.9 DL + Ex - 0.3 Ey	Combination 4-2
13	0.9 DL - Ex + 0.3 Ey	Combination 4-3
14	0.9 DL - Ex - 0.3 Ey	Combination 4-4
15	0.9 DL + 0.3 Ex + Ey	Combination 4-5
16	0.9 DL + 0.3 Ex - Ey	Combination 4-6
17	0.9 DL - 0.3 Ex + Ey	Combination 4-7
18	0.9 DL - 0.3 Ex - Ey	Combination 4-8

Pushover analysis is performed to evaluate the critical column from the structure and compared with GSA method for checking the biggest contribution of removal of several columns.

4 Modeling and analysis

4.1 Design standard

The design is based on SNI 03-2847-2013 Structural Concrete Requirements for Building Structure [5] and SNI 1726-2012 earthquake resistance planning procedures for building and non-building structures [2]. The load is given based on SNI 1727-2013 concerning the minimum load for the design of buildings and other buildings [4].

4.2 System and geometry structure

The structure of the building reviewed in this study consists of a regular structure and irregular structure. Each structure consists of 10 floors which have a height between levels 3.6 m, with the span between columns 4 m, and area of building 256 m². The top and front view in the regular and irregular structure can be seen in Fig. 1 below.

Fig. 1. The structure of regular building (a) top view and (b) front view. The structure of irregular building (c) top view and (d) front view.

4.3 Analysis of progressive collapse

4.3.1 Analysis of internal forces and progressive collapse in regular structure

Fig. 2. Removal of columns (a) the side column of structure No. 21, (b) the corner column of structure No. 41, (c) the column with largest P No. 161 and (d) the critical column of pushover analysis in columns 281, 291, 301, 311 and 321.

Analysis of progressive collapse of regular structures with the removal of columns on the first floor is based on GSA methods on long and short sides of the structure, corner structure [3] and remove column with most significant P values from pushover method analysis results. Also, the analysis is performed before column deletion is used as a comparison of the results. The location of the removal column can be seen in Fig. 2. Inner forces in regular column structures based on the largest P value with DCR value as an indicator of progressive collapse can be seen in Table 3.

Table 3. Inner forces and DCR values in column of regular structure.

1. Before removal of column (original)								
Load	Column	Combination	P ₁ (KN)	M2 (KN-m)	M3 (KN-m)	DCR Pu/Pn		Remarks
Gravitation	161	2) 1.2 DL+1.6 LL	-1973.048	-3.462E-14	6.474E-14	0.415		Safe
GSA	161	GSA 2(DL+0.25LL)	-2738.623	-4.93E-14	9.743E-14	0.576		Safe
Earthquake	161	10) 1.2 DL+LL– 0.3Ex–Ey	-1820.798	-68.2858	-20.4857	0.382		Safe
2. Removal of column on the side structure								
Load	Column	Combination	P ₂ (KN)	M2 (KN-m)	M3 (KN-m)	P ₂ /P ₁	DCR Pu/Pn	Remarks
Gravitation	91	2) 1.2DL+1.6LL	-2697.934	26.788	3.78E-14	1.367	0.567	Safe
GSA	91	GSA 2(DL+0.25LL)	-3823.438	39.7429	5.614E-14	1.396	0.804	Safe
Earthquake	91	8) 1.2DL+LL+ 0.3Ex-Ey	-2571.800	-42.3241	62.1946	1.412	0.540	Safe
3. Removal of five critical columns of pushover analysis								
Load	Column	Combination	P ₃ (KN)	M2 (KN-m)	M3 (KN-m)	P ₃ /P ₁	DCR Pu/Pn	Remarks
Gravitation	231	2) 1.2DL+1.6 LL	-3887.061	4.1223	-6.504E-13	1.970	0.817	Safe
GSA	231	GSA 2(DL+0.25LL)	-5600.729	7.0358	-9.609E-13	2.045	1.178	Collapse
Earthquake	231	7) 1.2DL+LL+ 0.3Ex+Ey	-3800.331	83.5421	66.9472	2.087	0.799	Safe

According to Table 3, progressive collapse does not occur in columns of regular structures following removal of several columns. The largest DCR value occurs on the removal of five critical columns according to pushover analysis results with DCR value of 1.178 in column 231 with 2(DL+0.25LL) load combination; the largest DCR value when removal of a single column occurs on removal of a column on the side of the structure with DCR value of 0.804 at column 91 with 2(DL+0.25LL) load combination. The location of columns 231 and 91 on the first floor can be seen in Fig. 3. The inner forces of beam in the regular structure with the largest M3 value can be seen in Table 4 below. Based on Table 4, progressive collapse occurs on beams of regular structures with removal of several columns. The largest DCR value is 4.665 with the removal of five critical columns based on

Table 4. Inner forces and DCR values of regular beam structures.

1. Before removal of column (original)								
Load	Beam	Combination	P ₁ (KN)	M2 (KN-m)	M3 (KN-m)	DCR Mu/Mn	Remarks	
Gravitation	1835	1) 1.4DL	0	0	-28.893	0.259	Safe	
GSA	1835	GSA 2(DL+0.25LL)	0	0	-42.255	0.379	Safe	
Earthquake	1250	9) 1.2DL+LL-0.3 Ex+Ey	0	-3.345E-16	-83.499	0.749	Safe	
2. Removal of column on the side structure								
Load	Beam	Combination	P ₂ (KN)	M2 (KN-m)	M3 (KN-m)	M ₂ /M ₁	DCR Mu/Mn	Remarks
Gravitation	534	1) 1.4 DL	0	0	-83.727	2.898	0.751	Safe
GSA	534	GSA 2(DL+0.25LL)	0	0	-122.349	2.895	1.098	Collapse
Earthquake	1291	4) 1.2DL+LL+Ex- 0.3Ey	0	1.742E-17	-130.827	1.567	1.174	Collapse
3. Removal of five critical columns of pushover analysis								
Load	Beam	Combination	P ₃ (KN)	M2 (KN-m)	M3 (KN-m)	M ₃ /M ₁	DCR Mu/Mn	Remarks
Gravitation	494	1) 1.4 DL	0	0	-355.361	12.299	3.190	Progres- sive
GSA	494	GSA 2(DL+0.25LL)	0	0	-519.714	12.299	4.665	Progres- sive
Earthquake	494	8) 1.2DL+LL+0.3 Ex-Ey	0	1.282E-15	-353.093	4.228	3.169	Progres- sive

to the pushover analysis results on beam 494 with $2(DL+0.25LL)$ load combination. With single column removal, the largest DCR value is 1.174. This indicates that, with the removal of a single column, progressive collapse does not occur in the structure. The location of beam 494 on the first floor and beam 1291 second floor can be seen in Fig. 3.

4.3.2 Analysis of internal forces and progressive collapse in irregular structure

Fig. 4 below shows the results of the pushover analysis of the progressive collapse of irregular structures with removal of columns based on the GSA method of (a) the column in the middle of the top horizontal span; (b) in the middle of the left vertical span; (c) the right vertical span; (d) the top left corner; (e) the top right corner; (f) the lower left corner; (g) the middle corner of the structure; (h) the column with the most significant P; and (i) the critical column of the pushover analysis.

Fig. 4. Removal of columns of irregular structure.

The inner forces and DCR values in the columns of irregular structure can be seen in Table 5 below.

Based on Table 5, progressive collapse does not occur in columns of irregular structures following the removal of several columns. The largest DCR value happens with the removal of four critical columns from the pushover analysis results with DCR value of 1.071 in column 151 with $2(DL + 0.25LL)$ load combination and the largest DCR value when removal of a single column on the left vertical span of the structure is 0.812 with $2(DL + 0.25LL)$ load combination. Column 151 on the first floor can be seen in Fig. 5 below.

Fig. 5. Location of column and beam with the largest DCR.

Table 5. Inner forces and DCR values in columns of irregular structure.

1. Before removal of column (original)								
Load	Column	Combination	P ₁ (KN)	M2 (KN-m)	M3 (KN-m)	DCR Pu/Pn		Remarks
Gravitation	91	2) 1.2DL+1.6LL	-1946.089	-0.2258	-0.521	0.409		Safe
GSA	161	GSA 2(DL+0.25LL)	-2752.625	-2.2905	-2.290	0.578		Safe
Earthquake	91	9) 1.2DL+LL– 0.3Ex-Ey	-1821.471	-66.0779	-43.752	0.383		Safe
2. Removal of column of left vertical span								
Load	Column	Combination	P ₂ (KN)	M2 (KN-m)	M3 (KN-m)	P ₂ /P ₁	DCR Pu/Pn	Remarks
Gravitation	151	2) 1.2DL+1.6LL	-2712.914	-0.8464	27.204	1.394	0.570	Safe
GSA	151	GSA 2(DL+0.25LL)	-3861.413	-1.176	40.339	1.403	0.812	Safe
Earthquake	151	5) 1.2DL+LL+Ex +0.3Ey	-2605.613	48.7804	-39.167	1.430	0.548	Safe
3. Removal of four critical columns of pushover analysis								
Load	Column	Combination	P ₃ (KN)	M2 (KN-m)	M3 (KN-m)	P ₃ /P ₁	DCR Pu/Pn	Remarks
Gravitation	151	2) 1.2DL+1.6LL	-3557.781	29.7773	-46,766	1.828	0.748	Safe
GSA	151	GSA 2(DL+0.25LL)	-5093.928	44.5075	-67.944	1.850	1.071	Collapse
Earthquake	151	7) 1.2DL+LL+0.3 Ex+Ey	-3387.569	114.6787	-22.005	1.859	0.712	Safe

The internal forces of beam in the irregular structure with the largest M₃ value can be seen in Table 6 below. According to Table 6, progressive collapse occurs in beams of irregular structures with the removal of several columns. The largest DCR value is 3.44 with the removal of four critical columns from the pushover analysis results on beam 201 with 2(DL + 0.25LL) load combination. With a single column deletion, the largest DCR value is 1.175, which occurs on beam 440, and progressive collapse does not occur in the

structure. Beams 201 and 440 are located on the first floor, the location of which can be seen in Fig. 5.

Table 6. Inner forces and DCR values in beam of irregular structure.

1. Before removal of column (original)								
Load	Column	Combination	P ₁ (KN)	M2 (KN-m)	M3 (KN-m)	DCR Pu/Pn	Remarks	
Gravitation	1835	1) 1.4DL	0	9.755E-17	-29.386	0.263	Safe	
GSA	1835	GSA 2(DL+0.25LL)	0	1.394E-16	-43.016	0.386	Safe	
Earthquake	1247	8) 1.2DL+LL+0.3 Ex-Ey	0	-1.12E-15	-77.572	0.696	Safe	
2. Removal of column of upper left corner structure								
Load	Column	Combination	P ₂ (KN)	M2 (KN-m)	M3 (KN-m)	P ₂ /P ₁	DCR Pu/Pn	Remarks
Gravitation	440	1) 1.4DL	0	0	-90.455	3.078	0.812	Safe
GSA	440	GSA 2(DL+0.25LL)	0	0	-130.951	3.044	1.175	Collapse
Earthquake	449	8) 1.2DL+LL+0.3 Ex+ Ey	0	-1.742E-17	-127.145	1.639	1.141	Collapse
3. Removal of four critical columns of pushover analysis								
Load	Column	Combination	P ₃ (KN)	M2 (KN-m)	M3 (KN-m)	P ₃ /P ₁	DCR Pu/Pn	Remarks
Gravitation	201	1) 1.4DL	0	0	-262.367	8.928	2.355	Progres- sive
GSA	201	GSA 2(DL+0.25 LL)	0	-8.71E-18	-383.617	8.917	3.443	Progres- sive
Earthquake	201	10) 1.2DL+LL-0.3 Ex-Ey	0	-3E-16	-246.789	3.181	2.215	Progres- sive

4.4 Predicted type of progressive collapse

Progressive collapse is divided into pancake-type, zipper-type, domino-type, section-type, instability-type and mixed-type collapse [1]. Each type of progressive collapse has a characteristic. In unplanned situations like an earthquake, pancake type offers little opportunity to save people because the collapse occurs very quickly. This is in contrast to the domino type that occurs gradually and provides a more significant opportunity to

protect people. In the demolition of old buildings, a prediction for the information pattern and direction should be obtained before the demolition of the building to see the effect of destruction on other buildings.

4.4.1 Predicted type of progressive collapse of the regular structure

The collapse pattern based on results of progressive collapse analysis on the regular structure with the removal of five columns from pushover analysis results with $2(DL+0.25LL)$ load combination can be seen in Fig. 6 below.

Fig. 6. Pattern of regular structure collapse; (a) before running program and (b) after running program.

Based on the collapse pattern, it can be seen that the removal of five columns causes overturning in the next column, which triggers a failure or collapse of the building. The pattern of collapse that occurs corresponds to the pattern of progressive collapse of the domino type [1], so it is concluded that the regular structure is the progressive collapse of the domino type.

4.4.2 Predicted type of progressive collapse of the irregular structure

The pattern of collapse that occurs following the removal of four columns in an irregular structure can be seen in Fig. 7 below.

Fig. 7. Pattern of irregular structure collapse; (a) before running the program and (b) after running the program.

Removal of four columns causes overturning in the next column, thus triggers subsequent failure of the buildings. The pattern of collapse corresponds to the pattern of the progressive collapse of the domino type, as in the regular structure analysis.

5 Conclusions

The progressive collapse in regular and irregular structures does not occur with single column deletion; progressive collapse only happens after the removal of some of the critical columns resulting from the pushover analysis. In a regular structure, the largest DCR value of progressive collapse occurs with the removal of five critical columns from pushover analysis on the side of the structure with 2 (DL+0.25LL) load combination, which happens in beam 494 with a DCR value of 4.665. In the regular structure, the largest DCR value of progressive collapse occurs with the removal of four critical columns in the middle horizontal span according to pushover analysis result with 2(DL+0.25LL) load combination in beam 201 with a DCR value of 3.443. Based on the collapse pattern, regular and irregular structures have a progressive collapse of a domino type.

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