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PROGRESSIVE COLLAPSE RESISTANCE OF A 13-STORY RC BUILDING SUBJECTED TO DIFFERENT "MISSING COLUMN" SCENARIOS

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Abstract: *In this paper, the progressive collapse resistance of a typical 13-story RC framed structure is assessed. The building is subjected to three damage scenarios by the removal of a corner column from 1st floor, from 7th floor and from 13th floor. According to GSA (2003) Guidelines, nonlinear dynamic analyses are performed in the ELS® computer software, which is based on Applied Element Method. It was shown that, under the standard GSA loading = DL+0.25LL, the building is not expected to fail. Moreover, the 13-story structure collapses under the gravity loads 1.65(DL+0.25LL) when the corner column is removed from the 1st floor or from the 7th floor and under 1.80(DL+0.25LL) when the column is removed from the 13th floor.*

Key words: *Applied Element Method, damage scenario, nonlinear dynamic analysis, progressive collapse, RC framed building.*

1. Introduction

The progressive collapse is defined in the ASCE/SEI 7-05 [1] as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it". Also, the buildings should be designed "to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage".

The failure of the Ronan Point Building (London, 1968), the collapse of the Murrah Federal Building (Oklahoma, 1995) and the collapse of the World Trade Center (New York, 2001) drew the attention of the structural engineers in the prevention of the progressive collapse. U.S. General Service Administration and Department of Defense developed two guidelines: GSA (2003) [2] and DoD (2009) [3] for assessing the potential to progressive collapse of buildings. In 2013 there were published the new versions: GSA (2013) and DoD (2009) including the changes from 2013.

Experimental results [4-6] have shown that the reinforced concrete buildings seismically designed have an increased resisting capacity against progressive collapse initiated by the sudden removal of

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a column.

GSA (2003) Guidelines [2] recommends assessing the progressive collapse potential of a structure following the removal of a first-story column in four damage scenarios: an exterior column located at or near the middle of the short side (case C_1), an exterior column located at or near the middle of the long side (case C_2), a corner column (case C_3) and an interior column (case C_4). In addition, DoD (2009) Guidelines [3] provides for each plan location of the element removal, perform analyses for: first story above grade, story at mid-height, story directly below roof and story above the location of a column splice or change in column size.

In the authors' previous research [7, 8], the progressive collapse resistance of a 13-story RC framed building was assessed according to the GSA (2003) Guidelines [2]. It was found that, the structure is not expected to fail when a first-story column is suddenly removed, and the case C_3 is the most dangerous.

The main objective of this study is to evaluate the progressive collapse risk of the 13-story building subjected to three damage scenarios by the removal of a corner column from first floor, from seventh floor (story mid-height) and from thirteenth floor (story directly below roof) of the structure. The analyses are performed in the Extreme Loading® for Structure (ELS®) software, which is based on Applied Element Method (AEM).

2. AEM Model of the 13-Story Building

The present study is performed on a 13-story RC framed structure located in Brăila (a zone with high seismic risk from Romania). The existing building was designed in 1972 according to the former codes. The structural system of the building consists of five bays of 6 m in the longitudinal direction and two bays of 6 m in the transverse direction. The story height is 2.75 m, except for the first two stories which have 3.60 m, and the total height of the building is 37.45 m. The dimensions of the beams and columns are presented in Table 1 and the thickness of the slabs is 15 cm.

In addition to the self-weight of the structural elements, a dead load (DL) of 2.20 kN/m^2 is applied on the current floor and 2 kN/m^2 on the roof floor. Due to the exterior walls, a dead load of 6.50 kN/m is considered for the first floor exterior beams and 5 kN/m for the rest of the exterior beams. The live loads (LL) are: 2 kN/m^2 for the current floor and 2.50 kN/m^2 for the roof floor.

The 13-story RC framed structure was seismically designed according to the former Romanian code P13-70 [9]. The building is located in Brăila, which is situated in zone 8 of seismic risk, with the seismic coefficient k_s = 0.05. The magnitude of the total seismic force is S = 0.037G, where G is the total weight of the structure. The structural elements are detailed according to the former code for concrete structures STAS 8000-67 [10]. The concrete class used is B250 ($f_{ck,cube}$ = 22 MPa) and the steel types are: PC52 (f_{yk} = 340 MPa) for longitudinal reinforcement bars and OB38 (f_{yk} = 260 MPa) for transverse reinforcement bars. The reinforcement details of the beams, columns and slabs are not provided in this paper, these are given in the author's Ph.D. thesis [11].

Dimensions of the structural elements Table 1

Floor	Columns [cm]	Longitudinal beams [cm]	Transverse beams [cm]
1, 2	70x90	35x65	35x70
3, 4, 5	70x75	35x65	35x70
6, 7, 8, 9	60x75	30x65	30x70
10, 11, 12, 13	60x60	30x55	30x60

The validation of the numerical AEM model has been made simulating in the ELS® computer software an experimental test performed by Yi et al. [12] on a planar frame. The results obtained were presented in the authors' previous paper [8]. Recent studies [13, 14] have proved also that, the AEM method is an accurate, efficient and simple tool to predict the progressive collapse behavior of structures.

A three dimensional model of the 13-story RC framed building is generated in the ELS® computer software [15], where the reinforcement details of the structural elements are explicitly introduced. Beam elements are considered as T or L-sections. According to the building code requirements for structural concrete ACI 318-11 [16], the effective flange width on each side of the beam is taken by four times the slab thickness, value also adopted by Sasani et al. [17]. An isometric view of the 13-story AEM model is shown in Fig.1.

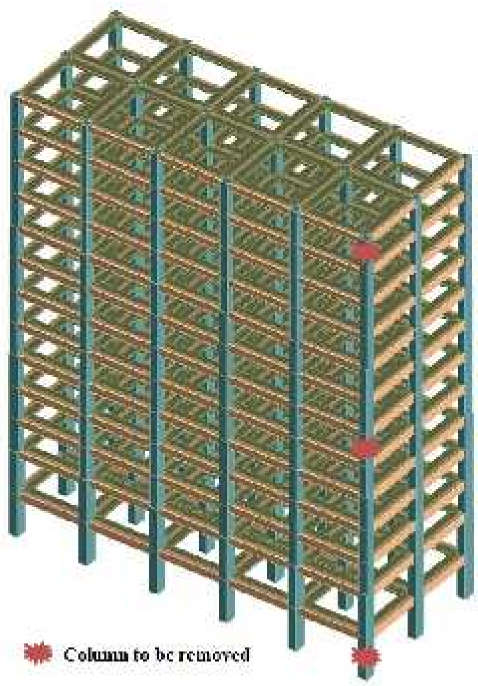

Fig. 1. *Isometric view of the AEM model*

3. Progressive Collapse Risk Assessment

3.1. Analysis Consideration and Loading Criteria

The progressive collapse risk of the existing 13-story RC framed building is assessed according to the GSA (2003) Guidelines [2]. The Alternate Path Method (AP) is recommended, which requires that the structure should be capable to bridge over the missing structural element. To determine the progressive collapse potential of a structure, the GSA (2003) Guidelines [2] provides three analytical procedures: linear static, nonlinear static and nonlinear dynamic. As the progressive collapse is a nonlinear and dynamic event, the nonlinear dynamic procedure is used in this study. For dynamic analysis, the following combination of loads shall be applied downward to the structure under investigation:

$$Load = DL + 0.25LL. \quad (1)$$

where, DL is dead load and LL is live load.

According to the GSA (2003) Guidelines [2], the material strengths (concrete compressive strength, yield and ultimate tensile strength for steel) are increased by a strength-increase factor of 1.25 to determine the expected material strengths.

To evaluate the progressive collapse potential of a building, the GSA (2003) Guidelines [2] recommends the removal of a first-story column in four damage scenarios: an exterior column located at or near the middle of the short side (case C_1), an exterior column located at or near the middle of the long side (case C_2), a corner column (case C_3) and an interior column (case C_4).

The 13-story existing building from Brăila was analyzed in all four damage scenarios recommended by the GSA

(2003) Guidelines [2] and the results are presented in the author's Ph.D. thesis [11]. The results have shown that the structure is not expected to fail through progressive collapse under the standard GSA loading = DL+0.25LL, when a first-story column is suddenly removed. For this reason, in the present study, the 13-story RC framed structure is subjected to other damage scenarios proposed by the DoD (2009) Guidelines [3].

The DoD (2009) Guidelines [3] provides for each plan location defined for element removal, perform AP analyses for:

1. first story above grade;
2. story directly below roof;
3. story at mid-height;
4. story above the location of a column splice or change in column size.

The new version of the GSA (2013) Guidelines does not contain these provisions. Thus, the existing 13-story RC framed structure from Brăila is subjected to the removal of a corner column from ground floor (C_3_1st floor), from 7th floor (C_3_7th floor) and from 13th floor (C_3_13th floor). In Fig. 1 are illustrated the positions of the columns that will be removed from the building under investigation.

3.2. Nonlinear Dynamic Analysis Results

To assess the progressive collapse resistance of the 13-story RC framed building, nonlinear dynamic analyses are performed in the ELS® computer software. For this type of analysis, according to the GSA (2003) Guidelines [2] the column must be removed in a time less than 1/10 of the period associated to the structural response mode for the vertical motion of the bays above the removed column. Thus, in the ELS® software the time removal is set to t_r = 5 ms and similar with Salem et al. [14] a time step of t_s = 1 ms is considered. A damping ratio of ξ = 5% is used, value also adopted by Sasani et al. [17, 18], Tsai and Lin [19].

The response of the structure regarding the vertical displacement of the node above the removed column over a time span of t = 3 s, for the three damage scenarios is presented comparatively in Fig. 2. It is observed that, under the standard GSA loading = DL+0.25LL, the 13-story building is not expected to fail when a corner column from different levels (1st floor, 7th floor and 13th floor) is suddenly removed.

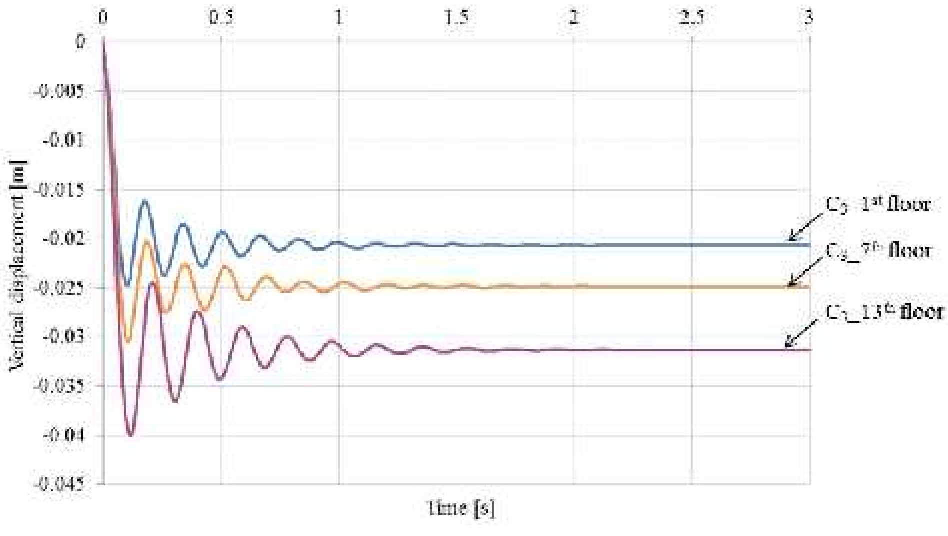

Fig. 2. *Time-vertical displacement curves for 13-story AEM model under DL+0.25LL*

The maximum vertical displacement obtained if a corner column is removed from the first floor is only Δ = 2.467 cm. For the case when the corner column is removed from the 13th floor, the maximum vertical displacement is Δ = 4 cm and when the corner column is removed from 7th floor is Δ = 3.05 cm. The highest value of the vertical displacement is obtained when the corner column from the last floor is suddenly removed from the structure.

As the 13-story building is not expected to fail under the standard GSA loading = DL+0.25LL, a series of nonlinear dynamic analyses are carried out to estimate the ultimate load-bearing capacity of the structure. For this, the gravity loads (given by Eq. 1) are gradually increased until the structure collapses. For the damage case in which a corner column from the first story is suddenly removed, eight nonlinear dynamic analyses are performed for the following gravity loads: 0.40(DL+0.25LL), 0.60(DL+0.25LL), 0.80(DL+0.25LL), 1.00(DL+0.25LL), 1.20(DL+0.25LL), 1.40(DL+0.25LL), 1.50(DL+0.25LL) and finally, under 1.65(DL+0.25LL) the structure fails.

The same eight analyses are carried out for the damage case in which the corner column is removed from the 7th floor, and it is observed that under the same gravity loads 1.65(DL+0.25LL) the structure collapses. When the corner column from the 13th floor is suddenly removed from the building, a total of ten nonlinear dynamic analyses are performed in the ELS® computer software for the gravity loads: 0.40(DL+0.25LL), 0.60(DL+0.25LL), 0.80(DL+0.25LL), 1.00(DL+0.25LL), 1.20(DL+0.25LL), 1.40(DL+0.25LL), 1.60(DL+0.25LL), 1.70(DL+0.25LL), and under 1.80(DL+0.25LL) the structure fails.

For each level of loads, the maximum values of the vertical displacement are collected to construct the capacity curve of the structure. In Fig. 3 are displayed the capacity curves obtained for the damage scenarios in which a corner column from the 1st floor, from the 7th floor and from the 13th floor of the building is suddenly removed.

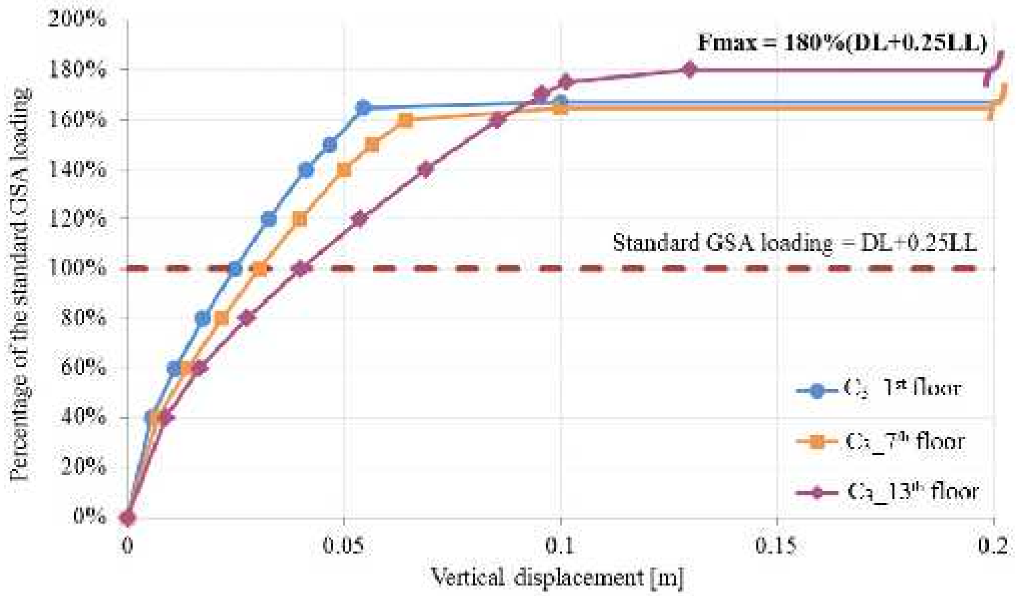

Fig. 3. *Capacity curves obtained for the 13-story building in the cases: C_3_1st floor, C_3_7th floor and C_3_13th floor*

In Fig. 3, the vertical axis represents the percentage of the standard GSA loading and the horizontal axis represents the vertical displacement of the node above the removed column. It is observed that, for the cases when the corner column is removed from the 1^{st} floor and from the 7^{th} floor, the structure fails under the same level of gravity loads: 1.65(DL+0.25LL). When the column is removed from the 13^{th} floor, the loads under that the building collapses are higher: 1.80(DL+0.25LL).

The failure of the 13-story AEM model under the maximum gravity loads is presented in Fig. 4: a) following the removal of a corner column from the first floor, under F_{max} = 1.65(DL+0.25LL); b) following the removal of a corner column from the 7^{th} floor, under F_{max} = 1.65(DL+0.25LL) and c) following the removal of a corner column from the 13^{th} floor, under F_{max} = 1.80(DL+0.25LL). Thus, a typical 13-story RC framed building fails under the same level of gravity loads if a corner column from the first story or from the story at mid-height is removed. For the damage scenario in which a corner column from the last floor is removed, the structure collapses under gravity loads with 9% higher.

In conclusion, it is important to analyze the damage scenario in which a column from the mid-height story of a building is removed, because it is as dangerous as the damage scenario in which the column is removed from the first story. This scenario is not explicitly provided in the new version of the GSA (2013) Guidelines.

The analyses presented in this study are performed in the ELS® computer software considering the structure composed by columns and beams. Beam elements are modelled as T or L-sections to include the effect of the slab. In this study, the full modelling of the slabs and their effect on the progressive collapse resistance capacity of the structure were not considered.

The results could be affected if the slabs are entirely introduced in the AEM numerical model. In their works, Helmy et al. [13] have performed a similar study on a 10-story reinforced concrete framed structure, subjected to the removal of a column from different levels of the building: first floor, fifth floor, eighth floor and tenth floor. When including the slabs in the analysis, the structure fails through progressive collapse only in the case when a corner column is removed from the tenth floor.

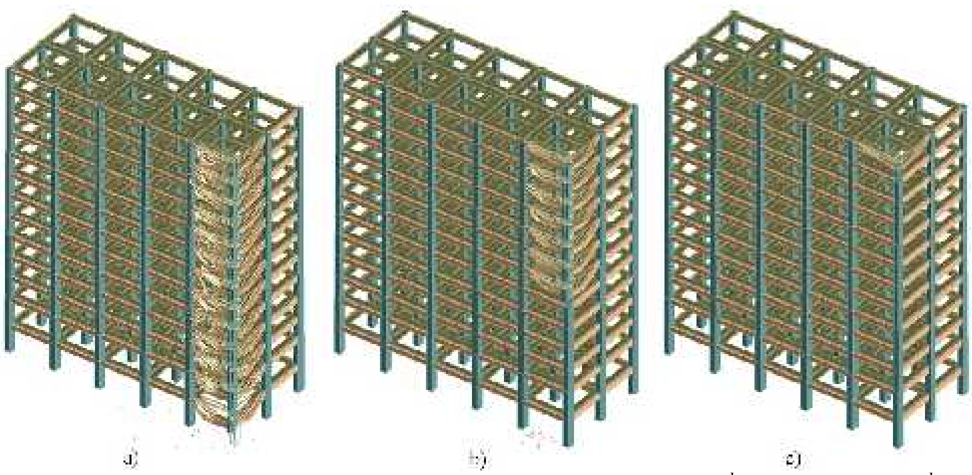

Fig. 4. *Failure of 13-story AEM model: a) C_3_1^{st} floor; b) C_3_7^{th} floor; c) C_3_13^{th} floor*

4. Conclusions

In the present study, the progressive collapse resistance of a 13-story reinforced concrete framed structure is investigated. The existing building from Brăila (a zone with high seismic risk from Romania) was designed 45 years ago according to the former seismic code P13-70 [9]. The structure is subjected to different damage scenarios by the removal of a corner column: from the first floor ($C_3\_1^{st}$ floor case), from the floor at mid-height ($C_3\_7^{th}$ floor case) and from the floor directly below the roof ($C_3\_13^{th}$ floor case). These damage cases are proposed in the DoD (2009) Guidelines [3].

According to the GSA (2003) Guidelines [2], a nonlinear dynamic procedure is applied to assess the progressive collapse resistance of the building. The results obtained in the ELS® computer software, which is based on AEM method, lead to the following conclusions:

1. The existing 13-story RC building is not expected to fail through progressive collapse under the standard GSA loading = DL+0.25LL, if a corner column from the first floor, from the seventh floor or from the thirteenth floor is suddenly removed.

2. Under the standard GSA loading = DL+0.25LL, the maximum vertical displacement of the node above the removed column is Δ = 4 cm for the $C_3\_13^{th}$ floor case, higher than that obtained for the $C_3\_7^{th}$ floor case, which is Δ = 3.05 cm and also higher than the maximum vertical displacement obtained for the $C_3\_1^{st}$ floor case, which is only Δ = 2.467 cm.

3. For the three damage scenarios, a total of 26 nonlinear dynamic analyses for different levels of loads have been performed to determine the ultimate load-bearing capacity of the structure. It was found that, the 13-story building collapses under the gravity loads 1.65(DL+0.25LL) when a corner column from 1^{st} floor or from 7^{th} floor is suddenly removed, and under the gravity loads 1.80(DL+0.25LL), higher with about 9%, when the corner column from 13^{th} floor is removed from the building.

4. In conclusion, it is important to consider in the progressive collapse analysis of structures also the damage scenario in which a column is removed from a mid-height floor, because it is as dangerous as the case in which the column is removed from the first floor of the building.

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