PROGRESSIVE COLLAPSE SCENARIO SIMULATION

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ABSTRACT: *This paper aims to predict the progressive collapse phenomenon for a building condemned for demolition. A progressive collapse scenario was agreed on after detailed structural analysis. The collapse of the building had to happen in such a way that it could not sever or affect the nearby buildings and railway in any way. Progressive collapse of a structure occurs when one or more major structural load carrying elements are removed and the remaining load bearing structural elements cannot support the weight redistribution and fail. The event is usually disproportionate and the failure of small elements may cause the collapse of a large part of the structure. A demolition scenario was decided and all the key failing structural elements were identified. A pushover analysis was done using FEM software to properly identify the falling direction of the building. With the data gathered from the analysis an animation was created and supplied to the demolition crew. The demolition was executed and a video was made to check the precision of the animation. After comparing the two it was agreed that the structure behaved similar with the animation model.*

KEYWORDS: *progressive collapse, demolition, safety and environment engineering, FEM, simulation*

1. INTRODUCTION

The progressive collapse of building structures is initiated when one or more vertical load carrying members (typically columns) is removed. Once a column is removed due to a vehicle impact, fire, earthquake, or other man-made or natural hazards, the building's weight (gravity load) transfers to neighboring columns in the structure. The columns cannot resist and redistribute the additional gravity load, which means 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 [1].

Progressive collapse is a very practical method used to demolish condemned buildings. Not long ago, engineers considered demolition through structural collapse to be more of an art then an actual science. This conception is changing rapidly due to the fact that certain breakthroughs in science allow engineers to take into account details once difficult to consider.

Today computational technologies like FEM (finite element method) and AEM (applied element method) offer better insight on this matter.

2. SCOPE AND OBJECTIVES

The focus of this paper is to evaluate the robustness of a building condemned for demolition using software simulation. After all the failing elements have been identified an animation software is used to coarsely reproduce the collapse of the detached elements.

The simulation was made using SAP2000 software, a powerful tool for hinged prediction. SAP2000 uses FEM which is not as accurate and as practical as AEM.

In short, the purpose of all this is to determine the falling direction of the building and make sure no debris damage neighboring structures or infrastructure.

3. SITE LAYOUT AND DEMOLITION REQUIREMENTS

The building in question is a depot/coal washing facility located in Petrila which has been abandoned after the coal mining industry declined in the early 90s.

In fig. 1, one may notice the layout of the facility and the building depicted in red which was scheduled for demolition.

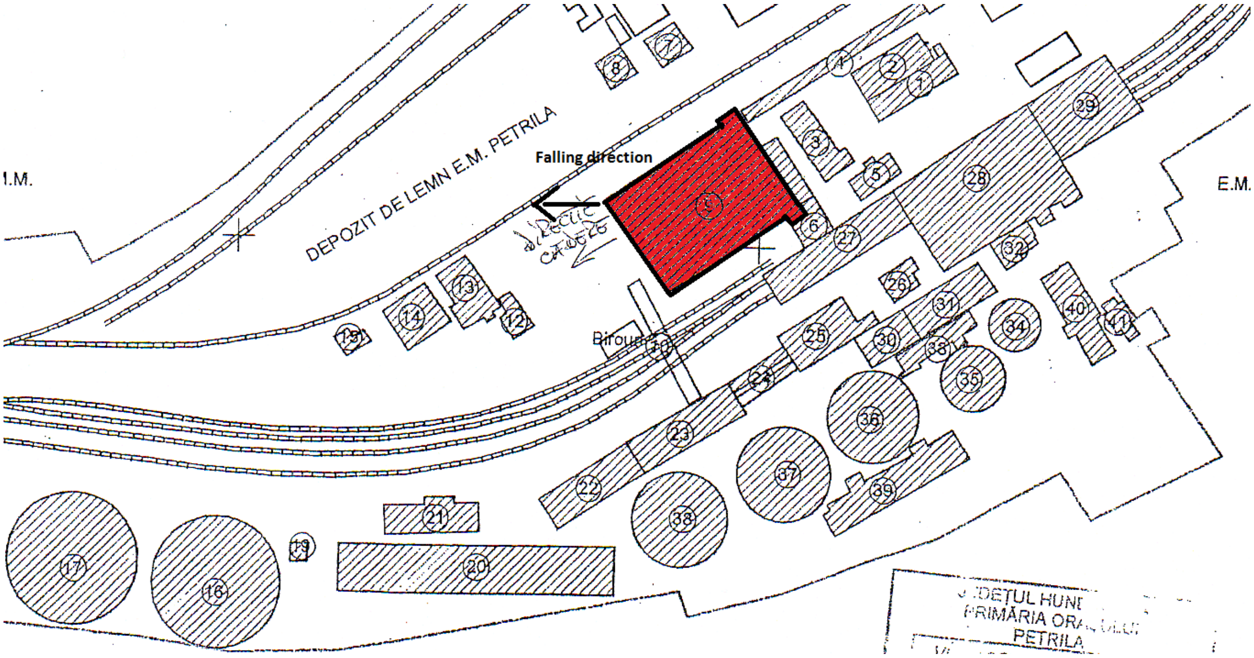

Fig. 1. Site layout and falling direction

The first problem the engineers on site faced, was collapsing only half of the building. This being the request of the owner.

The second problem was making sure that the debris from the demolished building would never fall and damage the surrounding buildings and most importantly it could not fall on the train tracks, especially since many carts and locomotives were stationed near by awaiting unloading.

In fig. 2 and 3 the proximity of the train tracks and the surrounding buildings is noticed. The other fact one may notice is that the building is irregular. This is an advantage mainly due to that fact that the falling direction coincides with the part of the building that is the heaviest and thus the momentum generated in the fall should help direct the debris in the desired direction.

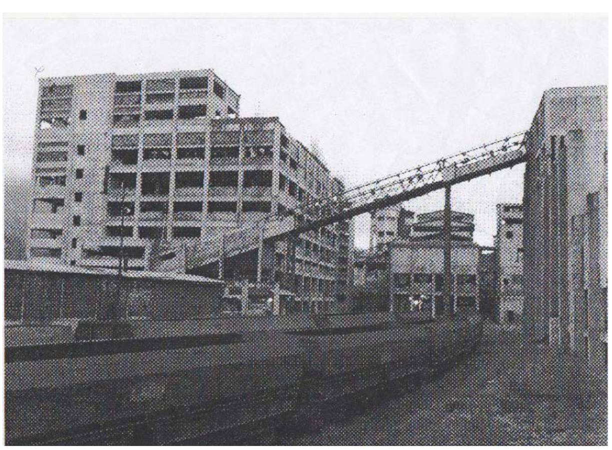

Fig. 2. North east view

Fig. 3. South west view

4. BUILDING DESCRIPTION

The building is a reinforced concrete rectangular frame structure with 8 stories having 7 openings of 5.5m and 9 spans of 6.3m with a total length of 39.3m over 57.5m. The top part is an annex which is 2 stories high distributed in a C shape.

The technical documentation was not available, therefore on site determinations were done on one of the beams and columns for each section to determine the concrete type and the reinforcement layout.

Table 1. Structural element characteristics

Type of element	Dimensions	Location	Longitudinal reinforcement	Confinement bars	Concrete type
Column	120x120	Exterior, ground floor	20ø28 evenly distributed	20ø11, 25cm spacing	B350
Column	80x80	Interior floors 1-3	16ø28 evenly distributed	20ø11, 25cm spacing	B350
Column	70x70	Interior floors 4-8, annex interior 9-10	16ø34 evenly distributed	20ø11, 25cm spacing	B350
Beam	40x60	All floors	10ø28; 4 top; 4 bottom;2 upper and lower center(fig. 4)	25ø10, 25cm spacing	B300

4.1. Explosives layout and detonation scenario

Explosives were laid out in 8 columns per row on 3 floors. A total of 84Kg of dynamite were used for the entire operation.

Every column was wrapped with a rubber band containing a wire mesh and geotextile with the purpose of reducing the overpressure caused by the shockwave and to stop the spreading of the resulting debris at great distance.

5. GUIDELINES FOR PROGRESSIVE COLLAPSE

This chapter discusses the progressive collapse guidelines after which the simulation was done. These guidelines have been implemented by the General Services Administration (GSA) in the United States of America in 2003. The guidelines are used to determine if a structure will be susceptible to progressive collapse. GSA recommendations and formulations for column removal are illustrated in various figures, and the Demand-Capacity Ratios (DCR) values for the building are presented. [2]

5.1. GENERAL GSA (2003) GUIDELINES

The GSA Progressive Collapse Analysis and Design Guidelines (2003) define analysis procedures to evaluate the vulnerability of a structure against progressive collapse. GSA (2003) recommends that a structure be analyzed by instantaneously removing a column from the middle of the traverse side of the building, near the middle of the longitudinal side of building, and at the corner of the building (Figure 5.1).

When analyzing the structure for progressive collapse potential, GSA (2003) recommends a general loading factor to be used for every structural member in the building being tested. GSA (2003) factors the loading conditions using Equation 5.1:

Load=2.0(Dead Load +0.25(Live Load)) (5.1)

Equation 5.1 is used for all loads acting on the structure, and increases the loading condition to account for irregularities in the structure. This equation presents the worst case scenario for the structure being tested for progressive collapse potential. Using Equation 5.1, the allowable extents of collapse resulting from instantaneous removal of primary exterior vertical supports are found in Table 2.

Table 2. GSA (2003) Allowable Extent of Collapse from Column Removal for Frame Buildings. [3]

Exterior Considerations	Interior Considerations
Maximum allowable collapse area shall be limited to:	
1. the structural bays directly associated with the instantaneously removed column	1. the structural bays directly associated with the instantaneously removed column
2. 167m2 at the floor level directly above the instantaneously removed column	2. 335m2 at the floor level directly above the instantaneously removed column
Which ever is the smaller area of the above 2	Which ever is the smaller area of the above 2

When vertical members are instantaneously removed, GSA (2003) uses Demand-Capacity Ratios (DCR) to analyze which structural members will exceed their loading capacity and lead to progressive collapse. Using the linear elastic static analysis, the DCR values are found using Equation 5.2.

$$\mathbf{DCR} = \frac{Mud}{\mathbf{Mce}(5.2)}$$

Mud = Acting force (demand) determined in component or connection/joint (moment, axial force, shear, and possible combined forces)

Mce = Expected ultimate, un-factored capacity of the component and/or connection/joint (moment, axial force, shear and possible combined forces)

Using the DCR criteria of the linear elastic approach, structural elements and connections that have DCR values that exceed the following allowable values are considered to be severely damaged or collapsed.

The allowable DCR values for primary and secondary structural elements are: DCR < 2.0 for typical structural configurations. [5]

6. SOFTWARE SIMULATION

The computation method used in this simulation was FEM. FEM is not the optimal choice to accurately reproduce a progressive collapse situation. Nevertheless, a FEM technique called staged construction was implemented. This way effort redistribution is considered by the software and the collapsing elements can be determined accurately.

6.1. AEM – FEM comparison

The main obstacle facing FEM when modeling structures is the modeling of large cracks and element separation. Although there are several FEM techniques that enable element separation, these are still limited to small problems with limited cracking and separation and cannot be generalized for use by practicing engineers in a full structural application. Using FEM, the element separation location can be either pre-defined by the user or automated; however, both solutions are impractical. Pre-defining the location controls the site of element separation, an event unknown in many cases, especially during structural collapse. Automation of element separation can be done using the Element Erosion Technique by removing damaged elements from the analysis when certain damage criteria are met. This also is not a practical solution as the crack width is limited to the element size and will cause cracks of large size that will never close in an application like earthquake loads. This solution will also not work when it comes to large scale problems when full structures are being modelled if we consider all of the elements to be close in size to the expected crack width.

The main advantages of using AEM center around its ability to reliably and accurately predict structural behavior beginning with the initial loading stages, into crack initiation, through propagation on to complete collapse. AEM's algorithms facilitate complex structural analysis without any user intervention and without artificial assumptions as to where or when cracks will occur.

6.2. SAP2000 simulation

For the simulation a static nonlinear analysis was conducted, using staged construction method. Only the dead load was considered with a vertical force of 2.5 KN/m2. The building was divided in 6 groups. Group 1 to 5 were the columns that were rigged with explosives, whereas group 6 was the building without the columns from the above mentioned groups.

Two load cases were considered:

- Dead load and 0.25 live load
- Staged construction

For the staged construction load case, 6 stages were implemented. First the structure was added and then the load. This is true for real life cases. In the second to the sixth stage each of the above mentioned 1 to 5 groups of columns were removed just like in the explosion stage scenario. This way the software can consider load redistribution and accurately compute element displacement.

Resulting displacements were high, the structural elements located at the extremities were collapsing and due to FEM limitations the analysis was ending prematurely. This meant that the behavior of elements located further from the extremities was not analyzed and no displacement data was available. To obtain data from all the affected elements in the structure, the dead load had to be reduced to a level were the strain from all the elements could be computed. The final reduction of the load was 70%. This way, the failure of the core elements can be noticed, meaning that anything more than 30% of the structure's dead load is sufficient for a successful progressive collapse of the building.

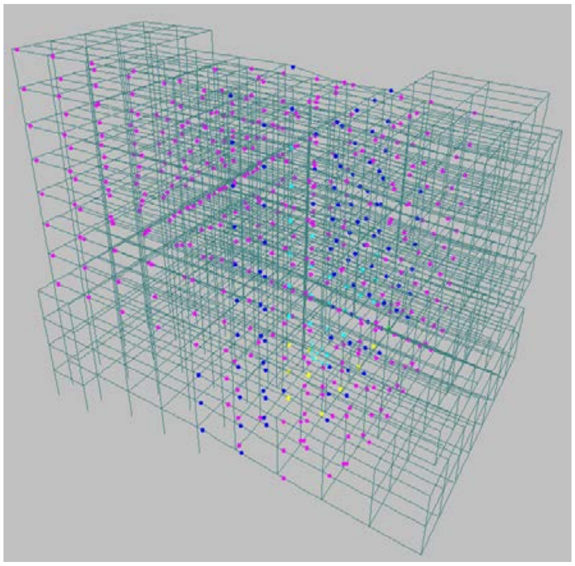

Fig. 5. Staged construction step 6

Fig. 5 represents the 6th step of the analysis. Here the deformation is visible and the yellow points show which elements may collapse. Cyan markers represent elements which are on the verge of collapse due to high deformation.

The joint which had the biggest displacement values was monitored and an X-Y vector was created. This vector is considered the falling direction (fig. 6). In Fig. 7 one can follow the Z axis displacement for each step.

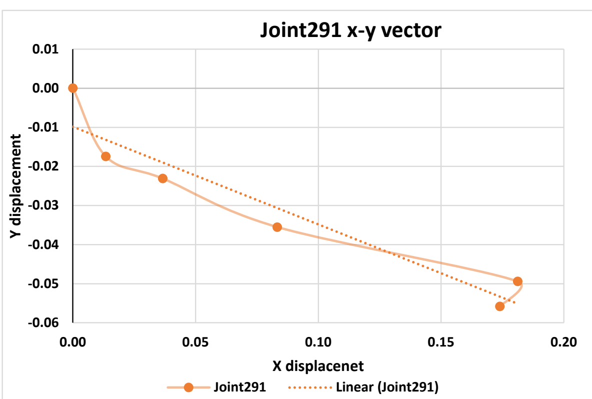

Fig. 6. X-Y vector for joint 291

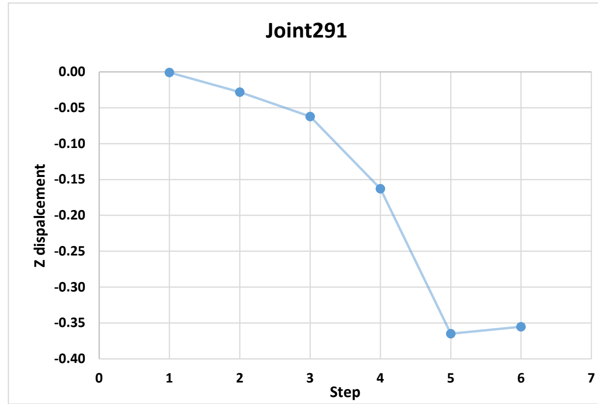

Fig. 7. Z axis displacement of joint 291

7. BLENDER ANIMATION

Since FEM software can't reproduce the collapse animation of a structure, I have tried to do so with animation software. The only difference is that the objects in the animation do not break and the ones expected to collapse are not tied together since fracture is not calculated by the software at hand. Nevertheless, the end result matches the captured video on site with great detail. The explosion in the animation was not iterated. However, just like in the SAP2000 simulation, the columns were removed in the same order with the 0.25s delay considered between detonation stages on site.

Fig. 8. Building collapse

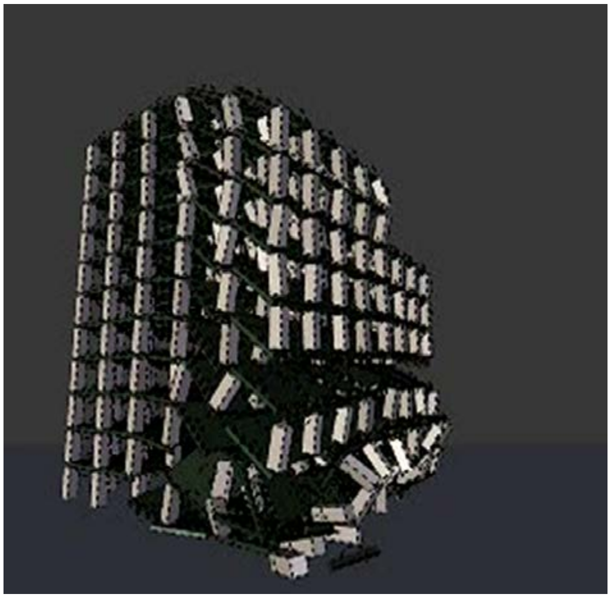

Fig. 9 Blender collapse simulation

8. CONCLUSIONS

In an article publicized on the American institute of steel construction website from the University of Ohio, a researcher tested in the laboratory and ultimately on a live building how accurate a SAP2000 progressive collapse simulation can be. The difference in strain results was approximately 21% [1]. It is not a small difference especially since less than 10% error can constitute a huge modification in behavior.

To try and obtain a more accurate response, animation software was used to reproduce what would happen after the elements start collapsing and confirm if the calculated fall direction is valid, or if certain unforeseen circumstances may change the outcome.

The results were accurate, the structure behaved as expected. Small wedging affected some collapsed elements but it did not change the falling angle. The demolition company considered this simulation a success.

9. REFFERENCE

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