CONTRIBUTIONS TO THE DESIGN OF CONTROLLED BUILDING DEMOLITION USING EXPLOSIVES

Pd.D. Thesis
- Abstract -

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1. Evolution and controlled demolition techniques state-of-the-art

The understanding of controlled demolition methods is closely related to the explosive products development, from the first use of the black powder, and the discovery of the dynamite by Alfred Nobel and nowadays. Through the history the utility of demolition passed from a subversive character (1605 – British Parliament demolition attempt) to a useful one (1900 Delaware City Hall demolition, Ohio, USA) such as at the end of XX century to be found as a profit generator activity. According to the technical means available, demolition may be classified as follows:

1. Mechanical demolition;
2. Thermal method demolition;
3. Demolition by expansion or explosion
4. Electrical and abrasive demolition.

The thesis only approached the demolition by explosion. Demolition technology always depended on the demolition entrepreneur and the complexity of every demolition was a consequence of the restraints required by the existing law. Due to the lack of scientific background or to some practical reasons, the demolition methods used by each company have become classified and formed the basis of exclusivity in the market. It has been noticed that, in Romania and in other countries, there are two main methods for building explosive demolition:

1. Vertical collapse method
2. Side collapse method.

2. Use of explosives

In order to induce the collapse, the explosion products will realize, in a controlled manner, a mechanical work within the structure. Directing the explosives’ enthalpy towards the critical points of the structure represents the core of the design activities related to a controlled demolition of a particular building. For a better understanding of how the explosives interact with the structural elements, it becomes necessary to consider those characteristics of explosives (listed below) that are able to describe their capability to transform internal energy into mechanical work:

I. Thermodynamic parameters:
   a. Oxygen balance;
   b. Specific volume and covolume;
   c. Heat and temperature of explosion;
   d. Explosions’ gases pressure. Explosive’s power.

II. Ballistic parameters:
   a. Mechanical work of explosion (potential);
   b. Detonating speed;
   c. Brisance.

III. Physical - chemical characteristics:
   a. Explosive charging density;
   b. Explosive’s humidity;
   c. Chemical stability.

IV. Safety parameters:
   a. Shock sensibility;
   b. Friction sensibility;
   c. Deflagration tendency;
   d. Thermoresistance.

These parameters will show which explosive shall be used for the design of a specific controlled demolition.
The following conclusions resulted:

- In the demolition process all excedentary supports should be removed by explosions in order to set the structural instability;
- The demolition process can be defined as the process of reducing the total number of supports to \((n-1)\), where \(n\) is the required number to guarantee the stability (Fig.2):

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Analyzing the use of the explosion energy it became a fact that only 25% of the total is the energy required by the useful purposes. The rest of about 75% is wasted, 36% absorbed by the environment as vibrations and 39% transferred as aerial shock waves. This excedentary energy requires special control and protection measures to be taken by the demolition company. The measures are different in nature when one will perform total or partial demolition (Fig.3).```
3. Structural design in the plastic range

The maximum collapse load, the minimum collapse load and the unique collapse load theorems were studied in order to identify which method will best provide answers on how the structure behaves after the equilibrium is broken.

An important output was that the loose of stability is triggered when the collapse load is reached either as a result of re-distribution or by transfer from the neighboring destroyed elements. The order of occurance of the plastic hinges is another important output of this analysis, allowing for the complete understanding of the structure’s collapse mechanism, which, in turn will give enough data to realize the prediction of the demolition mode. This mode will form up the criterion which, overlapped with the surrounding built-up environment, will determine the feasibility of the design. The biographical method, the combining mechanisms method and the independent moments method were studied and none of them has been proved as perfect match to the criterion, because of either the lack of determining the structural behavior after the loose of equilibrium or the complexity of the mathematical calculus.

A new method was identified and described in the paper: the applied Element Method (AEM), that offers the framework for easy establishing of both, occurrence of plastic hinges and the crack phenomena, so that the collapse mechanism of any structure can be defined. Basically the method consists of applying virtual springs in between two elements. So the structure is rigid but does not behave like a rigid body, which means that none of the elements in the network is deformable, but the assembly is.

Important for the method is the material model used for mathematical determination. It can be of a linear or non-linear load-displacement characteristic curve. It is important because the failure criterion consists of the failure of the virtual springs. The crack propagation is translated by this method as the enlargement of the areas where the springs have failed.

It has been demonstrated that there is a number of factors that may influence the accuracy of the method:
- The number of the elements in the network;
- The number of springs;
- The Poisson coefficient.

At the end of the analysis it is concluded that the AEM can be successfully employed for the controlled demolition design and it has a clear advantage against the Finite Element Methods. It can predict, with a good level of accuracy, the moment and the place the cracks will occurre and propagate, leading eventually to the building’s collapse.

In conclusion a single theoretical design method should allow for obtaining those results pertinent to a building demolition.

4. Selection of software

Bearing in mind the plastic range theory, the next step was to identify the adequate software to be used allowing for a high level of computational accuracy. The following programs were tested by modeling with them the same structure and comparing the results:
1. ANSYS LS DYNA;
2. ROBOBAT MILLENIUM;
3. EXTREME LOADING for STRUCTURES (ELS).

The last program was chosen, due to its capability to allow for a simulation beyond the failure point, for continuing calculations until the building is down, transformed in debris. Because ELS has not been accredited, more work was required by going through a validation & verification procedure (Fig.5). Validation is the process of determining the degree to which a model, simulation and the associated data are accurate representations of the experiments or real processes from the perspective of the controlled demolition. Verification is the process of establishing if a computer model and simulation accurately represent the demolitioner’s conceptual design and specifications.

The aim was to prove that the software can model and simulate, with a good level of accuracy, elementary situations, such as simply supported beams, etc. If the attempt is successful than it can be assumed that the software usage can be extended to more complicated cases.

A verification and validation process was initiated. An experimental set of data has been chosen to be compared with and the results (Shown in the thesis Annex) showed a good level of accuracy. The experiment consisted in submitting a group of 4 simply supported concrete reinforced beams (Table 1) to shear failure. The same beams were modeled with ELS and tested under the same conditions, to shear failure.

### Table 1. Tested beams

<table>
<thead>
<tr>
<th>Beam #</th>
<th>Ra</th>
<th>B</th>
<th>d</th>
<th>a/d</th>
<th>Shear reinforcement</th>
<th>Longitudinal reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>mm</td>
<td>mm</td>
<td></td>
<td>[mm]</td>
<td>[mm]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Φ [mm]</td>
<td>No. of bars/Φ [mm]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>a_e [mm]</td>
<td>µ_e [%]</td>
</tr>
<tr>
<td>H50/1</td>
<td>49.9</td>
<td>200</td>
<td>359</td>
<td>3.01</td>
<td>0</td>
<td>2Φ32</td>
</tr>
<tr>
<td>H50/2</td>
<td>49.9</td>
<td>200</td>
<td>353</td>
<td>3.06</td>
<td>Φ6/260</td>
<td>2Φ32</td>
</tr>
<tr>
<td>H50/3</td>
<td>49.9</td>
<td>200</td>
<td>351</td>
<td>3.08</td>
<td>Φ8/210</td>
<td>2Φ32</td>
</tr>
<tr>
<td>H50/4</td>
<td>49.9</td>
<td>200</td>
<td>351</td>
<td>3.08</td>
<td>Φ8/210</td>
<td>2Φ32+1Φ25</td>
</tr>
</tbody>
</table>

### Table 2. Experimental shear failure data sets V_{exp} versus the simulation data sets V_{ELS}

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
<th>Covariance</th>
</tr>
</thead>
<tbody>
<tr>
<td>H50-1</td>
<td>0.43</td>
<td>0.01</td>
<td>0.84</td>
<td>0.18</td>
<td>21.54%</td>
<td>559</td>
</tr>
<tr>
<td>H50-2</td>
<td>0.898</td>
<td>1.98</td>
<td>1.03</td>
<td>0.28</td>
<td>27.34%</td>
<td>2542</td>
</tr>
<tr>
<td>H50-3</td>
<td>0.39</td>
<td>1.17</td>
<td>0.98</td>
<td>0.21</td>
<td>20.88%</td>
<td>4405</td>
</tr>
<tr>
<td>H50-4</td>
<td>0.37</td>
<td>1.09</td>
<td>0.94</td>
<td>0.18</td>
<td>19.31%</td>
<td>6079</td>
</tr>
</tbody>
</table>

The ideal value for the V_{exp}/V_{ELS} is 1. Similar calculation was made for the displacement data sets. The average values, dispersed around the ideal value and the positive big number of the covariance led to the conclusion that the software is able to accurately model and simulate this process. A more complicated case was then studied: a real demolition was modelled and simulated, and a comparison has been made. The results, as shown in Fig.6, drove to the conclusion that ELS is capable of simulating building collapse with appropriate...
accuracy.

5. Building demolition ELS analysis

Chapter 5 was dedicated to the analysis of two demolition scenarios for a 8 stories block of flats (28.50 m height) with reinforced concrete frame structure. Based on the design details the ELS model was made, complying with all dimensions and materials (Fig.7). The two scenarios were: vertical collapse and side collapse.

- **Vertical collapse scenario**: The structural elements where to place the explosive charges were chosen in order to create locally elementary mechanisms within the structural elements. These were positioned symmetrically against the vertical-longitudinal plan of the building. To control the mechanisms development, each detonation stage was determined for allowing the dead load redistribution and the occurrence of plastic hinges.

  The loss of equilibrium was obtained as a result of the vertical movement of the gravitational volume. (Fig. 8)

  a. **The Control** of collapse is obtained by employing a delayed detonation scheme.

  b. The central sub-structure must be big enough in order to allow the catenary forces gravity generated to draw the lateral volumes towards an inside collapse.

  c. The gravitational volume forms when the first floor supports are destroyed and plastic hinges occur inside the transversal vertical plans at the upper levels;
d. The gravitational volume will be forced to move downwards by removing the afferent columns at the lowest floors. Basically the scenario consists of moving the gravitational substructure downwards and the lateral parts to rotate inwards (Fig. 7 b and 8);
e. Potential causes that may cause the designed collapse mechanism to fail must be identified and eliminated by adequate control or protection measures.

- On the same model the side collapse scenario was simulated using ELS. This scenario has certain advantages, however there are situations where the built up environment may set some constraints: only one collapse direction available, or the underground utilities infrastructure are sensible to seismic shock wave, so it has to be reduced, etc.

![Fig.9 Side collapse ELS spatial view](image)

During this scenario two stages of the process have been observed: **active stage** (Fig. 9 a) and **gravitational stage** (Fig. 9 b). During the active stage there were actions to gradually remove some structural elements in order to deny the dead load transfer to the basement and to force the structure to bend towards the required direction. The gravitational stage is when there are no more detonations and it is the gravity alone that accelerates the mechanism movement.

The conclusions from this analysis are the following:

a. **Demolition control** is achieved by obtaining such overloads within the structure that will not cut the steel reinforcement when the surrounding concrete is being broken;
b. The **direction** must correspond to an area that has enough space to accommodate the collapse;
c. A smaller average debris rubble diameter can be obtained when intermediate volumes at higher floors are created, fact that will ease the later loading and removal of the debris by mechanical means;
d. The **catenary forces** are the ways and means that will pull the structure to bend around a chosen row of columns;
e. **Structure's Center of Gravity** acceleration is the main effect of lowest levels columns removal;
f. **Elevator walls** play a decisive role when the building collapses. In order to avoid uncontrolled behavior of the structure during the collapse these must be weakened prior to the demolition.

During the two demolition scenario simulation, a thorough analysis of the load transfer mechanisms after the column removal has been completed. ELS allows for the calculation of the bending moment, shear or axial loads \((M,N,T)\) values at any point in the structure and at any time step. Employing comparative analysis of the structure's \((M,N,T)\) diagrams before and after the element removal it was possible to identify the mechanisms of the load transfer mechanisms. It was an easy method to determine the occurrence of the hinges and also permitted to see how these hinges became parts of locally formed structural mechanisms. By
this analysis it was possible to improve the scenario. Two possible means for improvement are listed below:

- To the improved scenario: the supports removal/keeping compared with the old scenario, when the elementary new formed mechanisms do not lead to a global structural (collapse) mechanism;
- The increase/decrease of the delaying time for a next detonation stage in order to allow/deny the occurrence of plastic hinges in specific areas.

6. Conclusions

In this chapter a review of the whole thesis has been made with the emphasis on some important conclusions from each previous chapter, remarks on the thesis achievements, the capitalization of the results of the thesis and author’s recommendations for the future research.

The thesis achievements can be grouped under the following four aspects:

A. Civil engineering theoretical design aspects adapted to the demolition requirements;
B. Rules for the working sequences when designing an explosive controlled building demolition;
C. Practical aspects relative to demolition simulations;
D. Scientistical articles and papers.

A. Some civil engineering theoretical design aspects adapted to the demolition requirements

1. Plastic range design fundamental theorems analysis from a demolition perspective;
2. By establishing a sequence of actions for explosions and gravity, to the explosive charges it was assigned the role of continuity interruption and of hinges insertion at structural critical points;
3. A crack occurrence is the moment when a plastic hinge starts to work in the same place;
4. The AEM allows to identify the place where the crack appears and the direction where it will develop the gap.

B. Rules for the working sequences when designing an explosive controlled building demolition

1. Vertical collapse mode choice and ELS validation; Side collapse mode choice and ELS validation;
2. Establish the criterion used in order to choose the design method. This method must meet the following requirements:
   a. It must be able to determine the order of occurrence of the plastic hinges;
   b. It must be able to identify the time step and the moment when the structure loose its stability and become a mechanism;
   c. It must be able to determine the dynamic behavior of the created mechanism.

C. Practical aspects relative to demolition simulations

1. With the AEM is possible to determine the time moment when the building starts to collapse, the element and the place where the cracks occur and the development of the clefts;
2. (M,N,T) diagrams analysis before and after elements removal (demolition stage) provide semnificative information in order to understand the strengths of the structure and the dead load redistribution mechanism;
3. ELS provide a good analysis environment for an explosive controlled building demolition;
4. The comparative analysis of an experimental data set and the corresponding ELS data set proved a good accuracy level when simulating;
5. The validation of the ELS programme for the sake of this study.
D. Scientific articles and papers

During the PhD study there were 3 papers issued by the author and 4 articles in three International Conferences (IASS 2005 - Bucharest and 2006 - Beijing) and one Romanian civil engineering magazine (*Construcții civile și industriale*, year VI, issue no. 69, nov 2005).

The papers titles are as follows:
1. Building explosive demolition – evolution and state-of-the-art
2. Specific and non-specific problems associated with buildings controlled demolition;

Results capitalization

The thesis presents by itself an immediate applicability for the structures demolition design or validation:
- The analysis of the reinforced concrete frame structures behavior during the collapse;
- Explosive specific calculations when designing a reinforced concrete frame structure demolition;
- Validation of the collapse mechanism prediction;
- Potential collapse mechanisms failure and indication of the areas of work in order to secure that specific mechanism;
- Progressive collapse analysis for reinforced concrete frame structures.

Future research recommendations

► A thorough analysis of the masonry and reinforced concrete walls structures demolition mechanisms;
► Environmental Protection active measures study and methods of implementation;
► Catenary forces influence on the development of the collapse mechanisms. The AEM re-consideration of the virtual springs behavior due to the fact that the adopted material model cannot exactly represent the behavior in that plastic range.
► The vertical collapse scenario not being unique, other scenarios may be studied.
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