USE OF APPLIED ELEMENT METHOD TO SIMULATE THE COLLAPSE OF A BUILDING

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The numerical simulation of a progressive collapse of structures is a very actual concern. Engineers are more and more interested in structures integrity estimation and collapse theory finding, in order to develop strategies for increasing or decreasing the progressive failure. A new method has been developed, for the last years, called Applied Element Method that has a large practicability for failure modeling. This method is used by „Extreme Loading for Structures" software.
This paper has two main goals: (i) a short presentation of the Applied Element Method in regard to the Finite Element Method and (ii) the presentation of the case study both as mathematical modeling and as demolition of structure.
The results show a good correlation between numerical simulation and real demolition of the structure.

Keywords: applied element method, modeling, simulation, demolition

1. TECHNICAL ASPECTS REGARDING "APPLIED ELEMENT METHOD"

With a development and utilization of about 60 years, with hundreds of references and thousands of applications, the finite element method is the most used one for structural analysis of continuum mediums.

In the last period occurred the necessity of studies concerning the response of structures subjected to earthquakes, blast-effects, unexpected impact forces and fire, that are known as extreme loading conditions. In addition to these, the controlled demolition of structures is more and more an actual concern. These types of loading conditions are followed by discontinuities in the structural system, so that parts of it became discrete elements. The finite element method cannot be applied for this stage of the structural system.

Beginning 1996, professors Hatem TAGEL-DIN (Institute of Industrial Science, The University of Tokyo, Tokyo, Japan) and Kimiro MEGURO (International Center for Disaster-Mitigation Engineering - INCEDE), have developed a new method for structure modeling. This is the "Applied Element Method" and it combines features from finite element and discrete element methods. The main advantage of this method is that it can track the structural collapse behavior passing through all stages of the application of loads, elastic stage, crack initiation and propagation in tension-weak materials, reinforcement yielding, element separation, element collision (contact), and collision with the ground and with adjacent structures. The time needed for a complete analysis is acceptable and the accuracy of the results is satisfactory. In literature there are many articles regarding this issue [Tagel-Din, H., Meguro, K., 1998, 1999, 2000, 2006].

In the following the applied element method [1 ÷ 6] is compared with finite element method [7].

Finite Element Method	Applied Element Method
The structure is modeled using lines and dummy plans that divide it in elements with determined dimensions and called finite elements. These elements are continuum and deformable mediums and adopt all material type and properties [7]. The connection of elements is compulsory to be performed in nodes.	The structure is modeled as an assembly of small elements, with special shape and determined dimensions. These types of elements do not deform, the change of their position is as a rigid medium. AEM elements are connected using the elements entire surface, through a series of

a. There are many types of finite elements used for meshing different structural components (uni, bi and tri-dimensional), fig. 1.1.

b. Two elements are connected in nodes. The number and the type of degree of freedom of the model depend on the type of finite elements used for modeling.

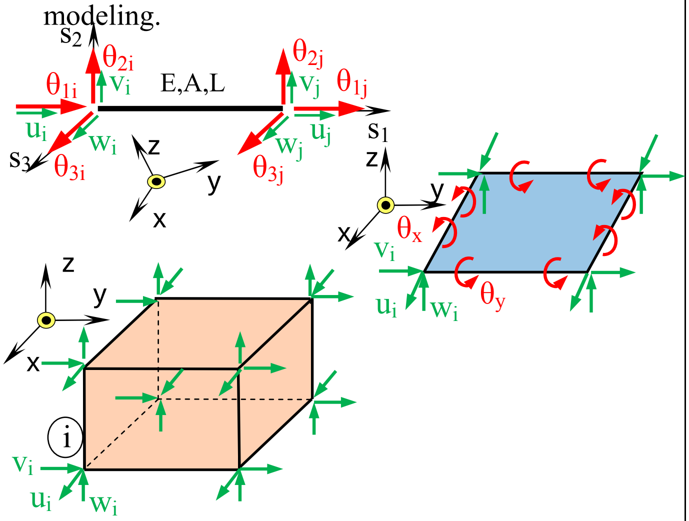


Figure 1.1 Types of finite elements

c. The connection of finite elements is allowed only in nodes and therefore transition elements are needed to switch from large sized elements to smaller elements, fig. 1.3.

connecting springs that adopt all material type and properties [2, 3, 5, 6].

a. There is a single type of element. There are used cuboids to model the structure to be analyzed, fig. 1.2.

b. Two elements are connected through a series of contact points. In every point are attached three springs: a normal spring and two shear springs. Each group of springs completely represents stresses and deformations of a certain volume and each element has six degree of freedom.

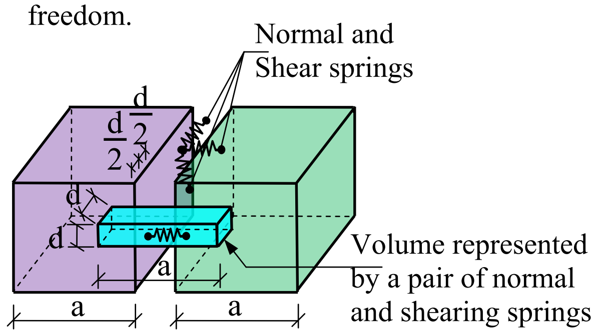


Figure 1.2 Applied element

c. There is no need for transition elements, it is allowed the partial element connectivity and the springs are generated at interface of elements, fig. 1.3.

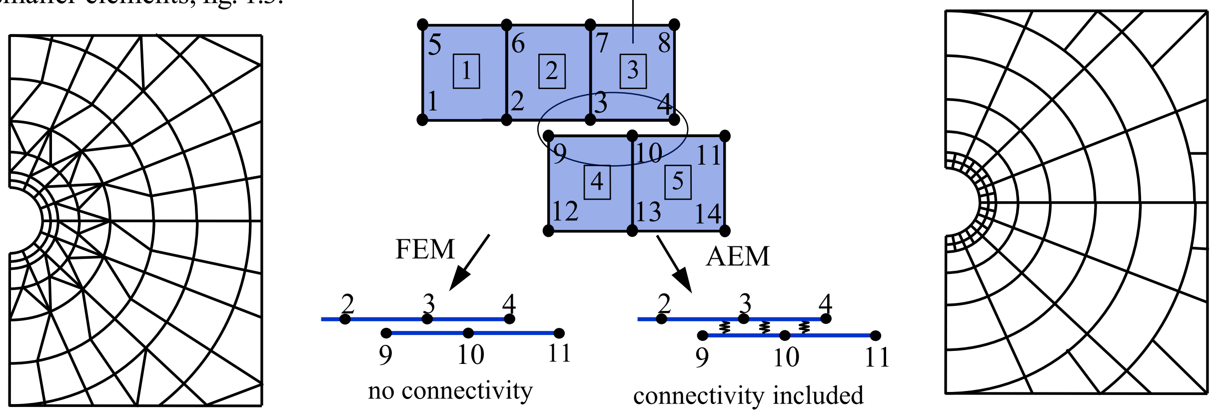


Figure 1.3 Connectivity

d. The global stiffness matrix [K], is determined based of contribution of each elements.

e. The medium is continuum. In order to model the failure of material you have to know the place where it is supposed the crack will be initiate, so that a node will be placed here and then elements are separated after successive calculations.

d. The global stiffness matrix [K], is determined as sum of contributions of all springs used for modeling the structure.

e. The using of this modeling method allowed that the initiation and propagation of cracks and the failure of the structure can be studied using only one initial model. The location of failure is determined during the cycling process.

2. PRACTICAL REALIZATION AND NUMERICAL DEMOLITION OF A BUILDING – CASE STUDY

There are many causes that can lead to progressive collapse of a structure [8]. More often than not this phenomenon is unwanted and more and more specialists are interested in study of it. The most of studies have a purpose of performing buildings less sensitive to progressive collapse. There is a special case and this is the controlled demolition using explosives of buildings [9]. In this case is needed the identification of that structural elements of building and them removal in a precise sequence, by successive explosions, at time intervals very well established, so that to lead to progressive collapse of structure in wanted conditions. All these tasks have to be performed using small explosive amount in order to reduce unwanted effects (aerial shock waves, fragments propulsion and seismic type waves) at minimum [10].

2.1 Structure description

The structure for demolition [13] was a reinforced concrete building with load-bearing walls and columns. The building had a rectangular shape with 17.50m and 7.60m plan dimensions and height of 33.40m, fig. 2.1. It had a bay of 5.95 m and five side spans between 2.35 and 4.25 m. The building was placed close to another building with a gap between them of 0.05 m. Facades were made by reinforced concrete walls and glass windows. The roof was made by reinforced concrete slabs fitted with thermal and water insulation. Stairs and the elevator were placed at south-west part of building.

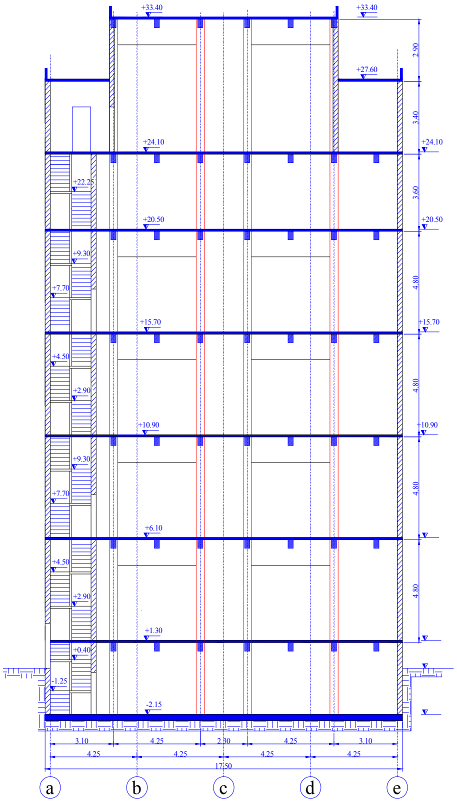


Figure 2.1 Cross section of building

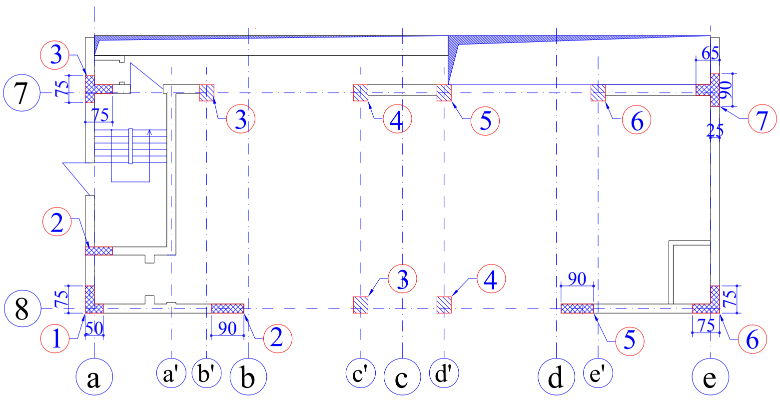


Figure 2.2 Plan of explosion steps

The structure consisted in reinforced concrete columns and walls stiffened through slabs. The reinforced concrete columns, with dimensions of cross section of 0.45x0.40 m, were centrally placed, whereas walls, with thickness of 0.25 m, were placed on contour. There are floors consisted in slabs with thickness of 0.15 m and a network of beams with dimensions of 0.25x0.55 m, respectively 0.25x1.00 m.

2.2 Practical realization of demolition

Preparation of building for demolition consists in uncoupling of construction from power, water and gases utilities and preparatory mechanical works. The first step in preparation is to clear any debris out of the building. Next, construction crews begin taking out non-load-bearing walls within the building. These steps are needed in order to minimize the consumption of explosive and thus to decrease aerial shock waves and fragments propulsion effects. Also, the clearing out of the bearing or nonbearing walls in this stage, is needed in order to create the necessary space to accelerate the dropping of structure in collapse initiation zone.

Grouping of explosives charges, in explosions steps, was established taking into account the dropping direction and the limitation of explosive amount per explosive step, as you can see in fig. 2.2 [13]. It can be seen that steps consist in one or more support elements in order to get the falling down direction and the acceleration of structure after collapse initiation. The time intervals among explosion steps were milliseconds range (0.025 s or more) and they were imposed by features of blasting caps used to set off the explosive charges placed into blast holes.

2.3 Numerical Evaluation

The numerical evaluation of controlled demolition using explosives was performed using Extreme Loadings of Structures (ELS) software [14]. This software use Applied Element Method (AEM) to simulate progressive collapse of structures.

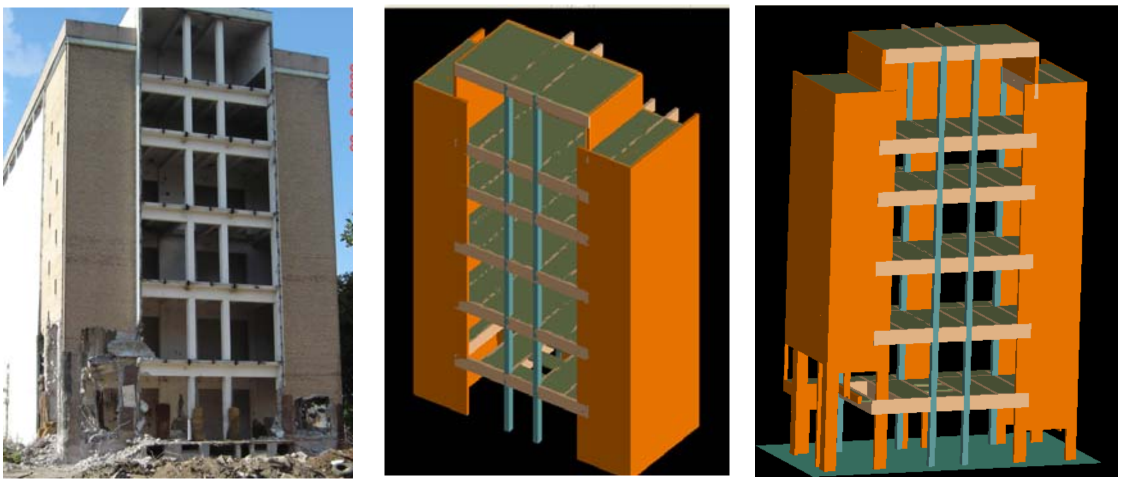
In order to simulate the demolition of building it was necessary to follow these steps:

(a) The geometrical modeling of building, fig. 2.3;

(b) A demolition scenario. This step consists in structural elements specification, sequence and time intervals among explosion steps, fig. 2.3. The sequence of elements destruction is presented in fig. 2.2. In this stage is indicated, also, the time of analysis and time step. For this analysis were used two values for time step: a time step of 0.001 s used in order to see the behavior of structure between two steps of explosion and a step of 0.01 s used to verify the dropping direction and the way of structure destruction;

(c) The integrity of structure verification and running analysis. For a time step of 0.001 s, with a Pentium (M) processor 2.0 GHz, it take more than 110 hours to reach 0.2 s for phenomenon, that can take more than 3 s;

(d) The verification and interpretation of results. In this stage were followed two aspects: (i) the mode of stress redistribution; (ii) the dropping direction and final destruction of structure.



a) b) c)

Figure 2.3 Real and simulated structure before demolition: a) real construction after preparatory works; b) geometrical model of structure; c) geometrical model of structure before starting simulation.

In order to see the way of loads redistribution there were chosen some points, indicated in fig. 2.4, and corresponding to these points there were determined displacements, fig. 2.5, and vertical forces, fig. 2.6 [11, 12].

After the curves of displacements were analyzed it can be made the following commentaries: **(i)** points where occur accentuated changing in downgrade correspond to moment of explosions (0.025 s, 0.050 s, 0.075 s, 0.100 s, 0.150 s, 0.200 s and 0.400 s) and thus to the moment of support elements destruction; **(ii)** the irregular form of displacement curve corresponding to first story longitudinal beam shows the exact moment when the support elements were demolished; **(iii)** curves corresponding to points 4 and 6 are almost identical because there are placed on a system like wall, that will be move on vertical direction without destruction until it hits the ground.

To better understand how the structure responded to the column removal and to study the propagation of deformation over the height of the structure, the variation of axial forces in the columns above the removed column was examined.

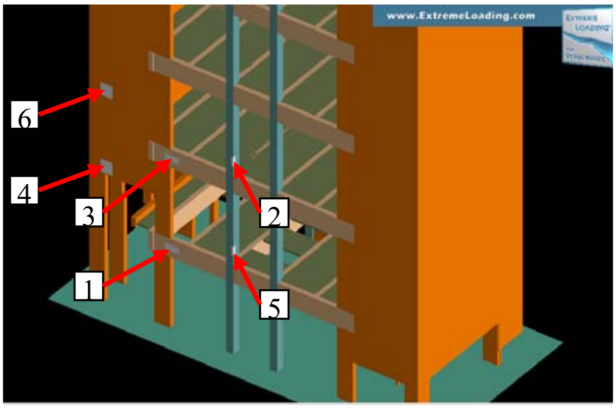


Figure 2.4 Points where displacements and vertical forces were determined

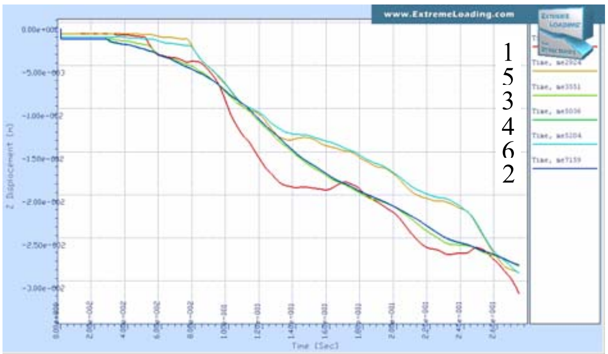


Figure 2.5 Displacements corresponding to points indicated in figure 2.4

Figure 2.6 Variation of vertical force corresponding to point 1, fig. 2.4

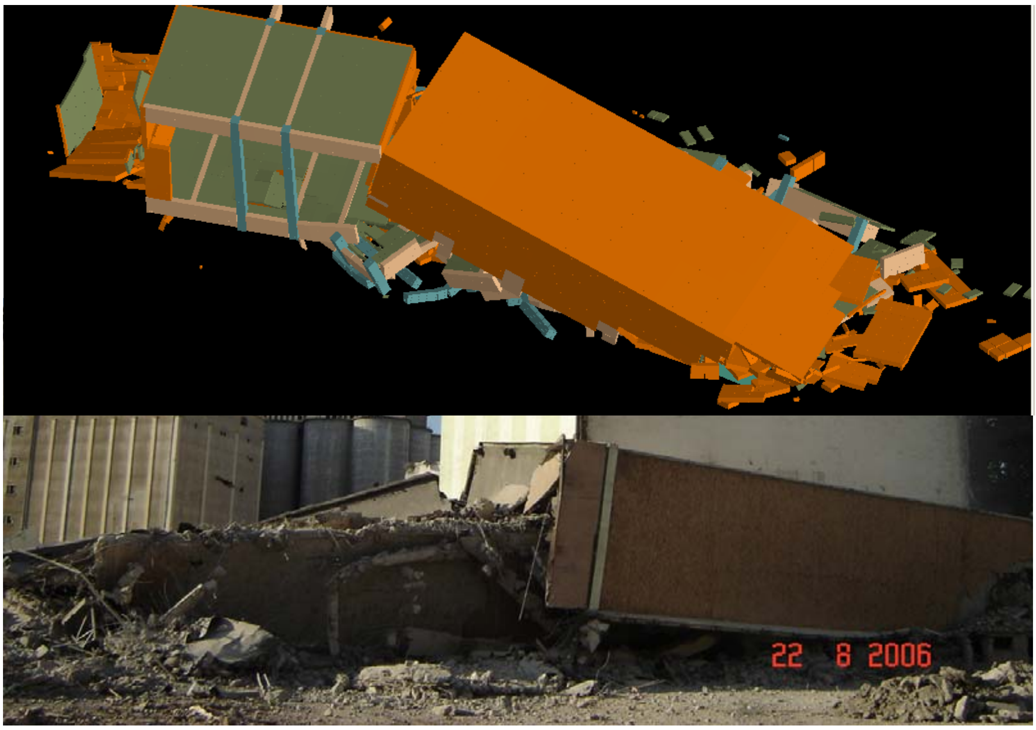


Figure 2.7 Numerical simulation and properly demolition

Analytical results showed that following an instantaneous removal of the first story column, for axes 8 and b', at time t=0.075 s, a sudden unbalanced force at joint in the second floor was formed, fig 2.6. This unbalanced force resulted in a high acceleration of joint and as a result, it started to move downwards and the second story column elongated, which in turn lead to the reduction of the axial compressive force in this column.

In terms of dropping direction and destruction of structure, after it hits the ground, the results of simulation are comparable with that obtained in the properly demolition, as it can be seen in fig. 2.7.

3. CONCLUSIONS

1. „Applied Element Method" combines features of Finite Element Method and Discrete Element Method, having as main advantage the possibility to describe the behavior of structure beginning with loadings application, initiation and propagation of cracks, elements separation until total collapse of the structure.

2. In order to see the way of loads redistribution there were chosen some points and corresponding to these points there were determined displacements and vertical forces. It can be seen that points where occur accentuated changing in downgrade correspond to moment of explosions and thus to the moment of support elements destruction.

3. It is shown that the joints above one of the removed columns, in two different floors, moved almost identically with the floor above having slightly smaller displacement.

4. The results show a good correlation between numerical simulation and real demolition of the structure.

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