Controlled Building Collapse Analysis and Validation

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Oktober 2007

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Abstract:

Demolition of buildings at the end of their life cycle has become more and more important. These buildings are either no longer attractive in an architectural sense or did not reach sufficient standards. Especially industrial buildings which are no longer used because of technological or business reasons are often demolished by controlled explosives. To avoid damage of neighboring buildings or traffic facilities an accurate prediction of the building collapse is needed. Otherwise uncontrolled collapse may cause a great physical and major collateral damage. In this contribution a global finite element model of a real world building is used to investigate the collapse sequence. A validation to prove the quality of the prediction has been carried out. The focus is laid on the influence of the failure criterion to the prognosis quality.

Keywords:

Building collapse, demolition by controlled explosives

1 Introduction

Controlled destruction of buildings at the end of their life cycle has become more and more important. These buildings are either no longer attractive in an architectural sense or did not reach sufficient standards. Especially industrial buildings which are no longer used because of technological or business reasons are often demolished by controlled explosives. To avoid damage of neighboring buildings or traffic facilities an accurate prediction of the effects of the building collapse and the building debris is needed. Otherwise uncontrolled collapse may cause a great physical and major collateral damage.

After several accidental events caused by apparently controlled demolition with explosives, the research unit FOR 500 [6] funded by the German research Foundation (DFG – Deutsche Forschungsgemeinschaft) has been formed. A main goal is the efficient and reliable prediction of controlled collapse of reinforced concrete buildings. Investigations are done in the fields of numerical methods, dealing with uncertainty data in numerical analysis, different modeling approaches and optimization of blasting strategies for buildings. Four civil engineering departments in Germany are included in this research unit.

The subproject in the focus of this contribution performed at Karlsruhe University has the goal to investigate the collapse sequence of the building by the Finite Element Method. The goal is to allow a detailed look at the phenomena which drive the problem and to investigate representative examples to create modeling rules for the discretization of rigid body models. One important point in these investigations is the validation of the numerical analysis to ensure the quality of the prediction.

As an example the demolition by controlled explosives of an industrial building is investigated. The commercial code LS-DYNA [3] is used for these investigations. The focus is set to the influence of the failure criterion and the validation on the basis of a video sequence.

2 Analysis concepts

The main problem of a demolition from the viewpoint of the engineer is that the dynamic structural behavior of the building during the collapse is not known. To give the engineer a tool for this prediction and to estimate the risk of a blast strategy the research unit 500 built up an analysis concept which investigates the important influences of the demolition by using explosives. The main goals are to produce a good a “priori” prognosis of the collapse belonging to a chosen blast strategy, as well as to consider uncertainties in geometrical and material data and to produce a computational tool for the practice. The concept considers different spatial levels and, as mentioned before, the uncertainties. Also, the verification and especially the validation of the results are important for the numerical analysis and are parts of the concept. The research unit is divided in four subprojects. Main goal of the project is an object oriented software system [9] for the multi-level simulation and optimization of the demolition process by controlled explosives of reinforced concrete structures.

Starting point of the investigations is the consideration of uncertainties. For the planning of a demolition information, particularly geometrical and material data, is not available or diffuse. This lack of information can be closed by special uncertainty algorithms [5], [10] which give the engineer the possibility to get good predictions in consideration of the variations of the solution due to uncertain data. The mathematical core of this uncertainty analysis is an optimization problem. This algorithm needs many deterministic solutions and is in this way well suitable for fast running models. One class of models, which reaches this condition, is a multi-body analysis. Here several rigid bodies are connected by springs with nonlinear characteristics. These nonlinear characteristics are defined by resistance curves, which are calculated with refined finite element models. A weak point in this analysis is the discretization level of the rigid body models. The discretization must be validated for a good prediction of the collapse. This means there must be a strategy to build up the models and to know were the hinges of the multi body system appear. To fix this lack, one subproject of the research unit has to do the validation process for representative real world demolitions. This is done by global finite element models [4], [7], [11].

The subproject which makes the validation of the global models must produce efficient and reliable predictions of the collapse. Here the finite element method and the central difference scheme for time integration are used. The focus of this contribution is the validation of a global finite element model of a demolition using controlled explosives.

3 Numerical example

For the numerical example a real world structure is chosen, which was demolished in 2000. It is one of the reference models of the research unit and is representative for industrial buildings, which are demolished by a toppling collapse. The buildup of the model, the numerical analysis including different model approaches and the validation sequence are described in the following sections.

3.1 Investigated structure

The investigated structure is an industrial building and was placed in Borna, Germany. Figure 1 shows the structure shortly before the blasting process. The building was part of a lime works and was used for storing. The base area of the structure is 36 m x 12 m at a maximum height of 25 m. All load carrying parts of the structure as well as six massive silo parts inside the building are made of reinforced concrete, the outer walls are built of masonry or they are simple concrete walls.

Figure 1: Investigated structure, Silo building at the lime works in Borna

The mass of the building, including all structural parts is estimated to approximately 3630 tons. The collapse, in the form of toppling over was achieved by removing the front side columns by controlled blasting (see figure 2). In order to make sure that the kinematics started correctly after the explosion the back side columns were additionally weakened by cutting parts of the reinforcements. Also parts of the inner thin concrete walls, which stiffened the structure, were removed before by conventional demolition techniques.

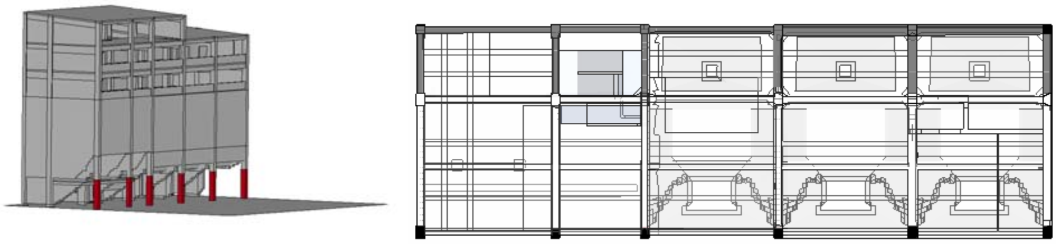

(a) (b)

Figure 2: Investigated structure; (a) blast strategy; (b) footprint of the building

Figure 2 shows at the left side a perspective view. At the lower front part the darker columns are removed by blasting. Also the wedges can be seen, which were removed conventionally and formed by removing parts of the load carrying structure to support the topple process. On the right side a footprint is shown. The light grey regions identify the parts which were pre-weakened by cutting the reinforcement. The black parts are the columns which are removed by blasting.

3.2 Computational model

In a first step a geometrical model was generated from technical drawings (see figure 3 (a)). The geometry was subdivided into typical civil engineering parts like girders, columns, floor plate, walls and the main part of the structure, the silo part (see figure 3, (c)). It is essential to create the geometry and to discretize the structure from 3D data because of the possibility of contact of building parts during the numerical analysis. To get a good prediction of the collapse sequence the real dimension of the building parts must be modeled to create the correct contact surfaces which were needed from the contact algorithm.

The 3D CAD model was discretized with approximately 75000 solid elements (see figure 3 (b)). An element edge length of approximately 30 cm and roughly cubic shapes of the elements were aspired for all elements. This special level of discretization was chosen between two limiting points. The discretization is as fine as it was needed to catch the surfaces of the building correctly and as coarse as it is needed to reduce the number of unknowns.
The chosen element formulation is a fully under-integrated hexahedral finite element (LS-DYNA element type 1, see [2]). The element formulation reduces the locking effect significantly. However, stabilization against unphysical kinematics, the so-called hourglass modes is necessary. Here the assumed strain co-rotational stiffness form developed by Belytschko and Bindemann [1] was chosen.

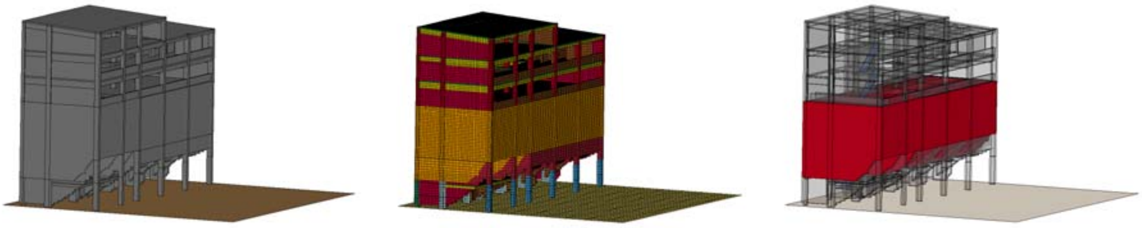

(a) (b) (c)

Figure 3: Investigated structure; (a) geometry model; (b) discretization; (c) highlighted silo part

The coarse mesh forces a simplified material description. Here a piecewise linear plasticity model is used (LS-DYNA MAT24). The formulation is certainly not able to reproduce the complex behavior of reinforced concrete on local level, but it already leads to reasonable results for a number of previous investigations in less complex systems [8]. The deformation in the range of moderate damage can be predicted in a good agreement. Detailed local effects are not investigated in this contribution. These effects are investigated in the research unit by another subproject [9]. Results of these investigations are used to create the material parameters of the used material routine.

The main problem which appears is the modeling of failure, especially if the structural parts are disconnected. The failure is included in the model via element erosion. This algorithm removes the element from the calculations if a mechanical value like stress or strain reaches a critical value. Within the analysis the plastic strains are chosen for the failure criterion. If the plastic strain of an element is greater than the chosen limit, the element is eroded; respectively the element is taken out of the analysis. However, it is noted than this simple application surely has some restrictions. As mentioned in the outlook section, current research is done to improve the handling of failure and separating of structural parts.

In reality, the collapse is initiated by the explosive removal of the front side columns, which is modeled in the simulation simply by removing the according elements. Previous investigations showed no influence of the shockwave caused by the explosion on the global kinematics. An influence of the shockwave resulting from the explosion is found only locally and can consequently be neglected in the coarse global investigations. Local effects concerning wave propagation are investigated in an-other project of the research unit.

The global collapse kinematics is characterized by innumerable contacts occurring during the simulation. Because of the unpredictability of the contact's location, they are all captured using an automatic segment-to-segment based penalty formulation.

3.3 Different modeling approaches

Two modeling approaches are investigated. The structure is split up in different structural parts. These parts are detached with the aforementioned material model and failure criterion for the erosion. Besides the typical structural parts there are two parts which are special. First, the silo part is a highly reinforced concrete structure and, second, the walls and columns in the ground floor also have a high rate of reinforcement.

Model A

Model B

Figure 4: Discretization approaches, Model A - silo as non eroding part, Model B - silo and columns in the middle axis as non eroding parts

The silo part has no direct influence on the starting collapse sequence, whereas the columns in the ground floor have. To investigate the influence of a possible failure of these columns two models are built up. Model A has no erosion option for the silo part, but all other parts have this erosion option. This model has the possibility to erode at the columns of the ground floor. Model B has no erosion option for the silo part and the columns at the ground floor. There is no possibility of erosion for the columns at the ground floor. These two models define the limiting point of failure or no failure (see figure 4).

3.4 Results

The results of this study are compared via internal and kinetic energy. From a video of the real demolition a main event is picked out and located in time. This event is the contact of the front part of the building to the ground and appears 5 seconds after the initiation of the blasting. At this time the kinetic energy must be reduced because the movement of the upper structure is stopped significantly. The kinetic energy of the moving structural parts is transferred into the structure after the impact to the ground and deforms the structure. In this way the internal energy rises up. This effect can be seen in figure 5.

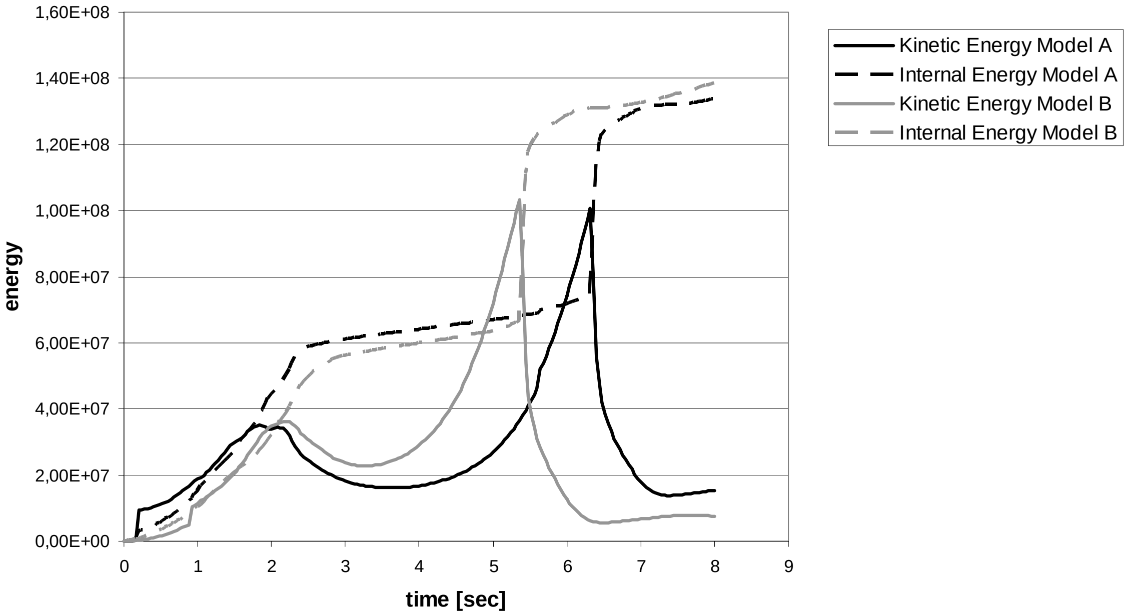


Figure 5: Internal and kinetic energies model A and model B

The results of this part of the investigations show the different behavior of the model if a critical part of it is modeled with and without an eroding option. The deviation arises from the different place of the rotational axis of the structure in the two approaches. As a final result it can be stated that model B, the model without an erosion option for the columns at the ground floor, is closer to the observation from the video. To confirm this conclusion, a validation via the whole video sequence is performed in the next section.

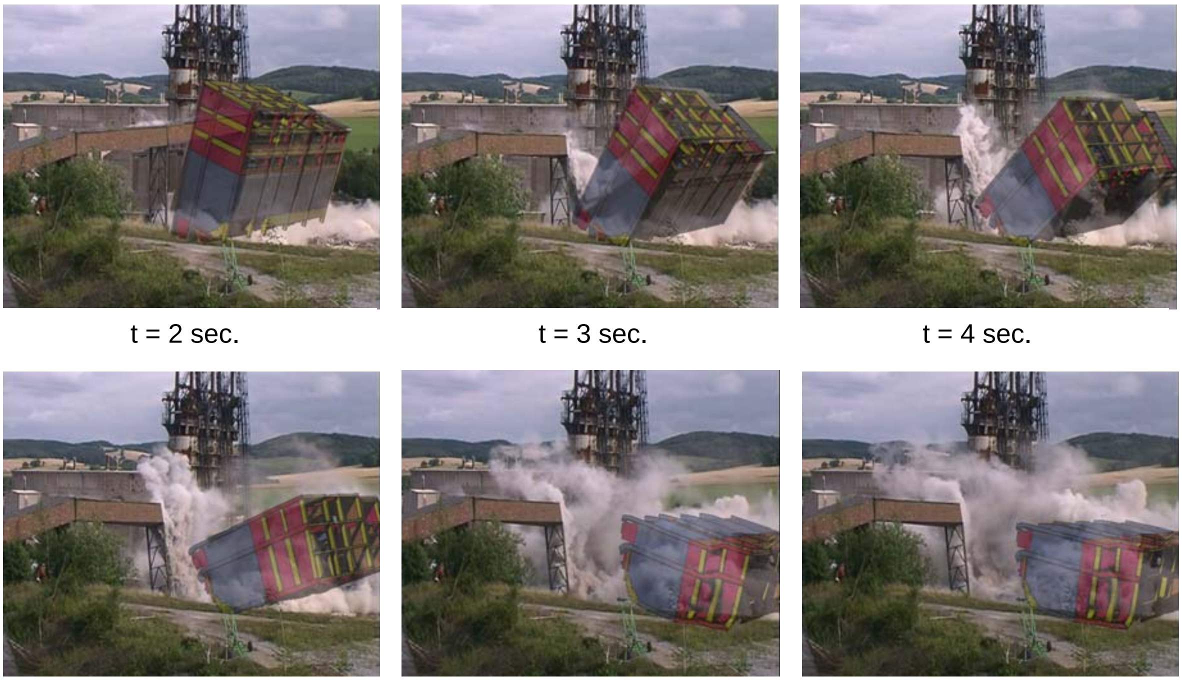
3.5 Validation

The validation of the numerical analysis is done via a video sequence. The investigated structure was demolished in 2000 and this makes it difficult to get any specific data for the validation process. The only documentation of the collapse is a video sequence, provided by the consultant which was responsible for the blast strategy. The sequence was recorded with a standard camcorder and used only for private documentation. To create a validation out of such a visual material, an overlay procedure is chosen. Frames from the video and images from the analysis results are combined to one image and the agreement is estimated. This procedure needs the knowledge of camera position and the axis of recording direction, respectively the view angle, to create the renderings of the numerical model in this particular perspective. The camera position and the view angle have been reconstructed by a graphical procedure on the basis of one frame of the sequence and some length measurements which were taken out of the technical drawings.

The overlay is done by first creating a perspective of the numerical analysis at a given time and making a transparency overlay with the frame of the sequence at the same time. In a second step a movie is created out of this single frame and the procedure is automated.

Figure 6 shows six overlays at different times. The results visualized here are from model B. This discretization approach makes the assumption that the silo and the middle row of columns are modeled without an erosion flag, respectively these structural parts are not taken out of the calculation. This assumption holds in the case of highly reinforced structural parts, which was proven by the technical drawings of the building.

The numerical analysis is in good agreement with the video sequence. The two representative events during the real world collapse are the first contact between the edge of the front part of the building with the ground (approx. 2 sec. after the blasting) and the contact of the whole front part of the building to the ground (approx. 5 sec after the blasting). These events are coinciding in time with the numerical results. Even the deformation of the upper three stories and the failure of the wall segments are similar.



t = 2 sec. t = 3 sec. t = 4 sec.

t = 5 sec. t = 6 sec. t = 7 sec.

Figure 6: Validation via video overlay sequence at different times after the blasting

It should be mentioned that the overlay in terms of the perspective is not working as well as it should. The images in figure 6 show a deflection in direction of the building length axis. This is an error which occurs through small differences in camera position and viewing angle of the real camera and the perspective in the render engine which are within the tolerance of the procedure of the derivation of this data. Nevertheless, the collapse sequence is described well from the numerical results. Especially the two aforementioned representative events occur in the numerical analysis at the same time as in the video sequence.

4 Conclusions and outlook

The goal of the investigations is to generate specific information about the collapse kinematics of buildings demolished by blasting. In this contribution a validation process is performed for an example of a reinforced concrete industrial structure with a toppling collapse sequence after the controlled blasting. Two model approaches are investigated which take into account the failure, especially the separation of structural parts. The approach without an erosion of the highly reinforced parts of the structure shows the best agreement with the validation data.

One of the main hypotheses which were proven by many video sequences of real world collapse of reinforced concrete structures is the appearance of local zones of high damages. These zones work in a mechanical sense like hinges in the region of large deformation and can split up in a finale stage of loading. Therefore the computational models must have the ability to reproduce these phenomena in the numerical analysis process. In this contribution the focus is laid on investigating the influence of the failure criterion to the prognosis quality by using element erosion. Further investigations should be done with different kinds of modeling failure, e.g. opening the connection of the elements at the nodes. This procedure has not the defect of losing mass and volume during the separation process. Another important point is the description of the failure criterion, especially the definition of separation, for reinforced concrete structures with coarse meshes.

5 Acknowledgments

This work is funded by the German Research Foundation (DFG) in association with the research unit FOR 500 ‘Computer aided destruction of complex structures using controlled explosives’. This support is gratefully acknowledged.
The video sequence and all necessary information about the investigated structure are due to courtesy of Dr.-Ing. Rainer Melzer, Planungsbüro für Bauwerksabbruch, Dresden.

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