Numerical Simulation of Controlled Building Collapse with Finite Elements and Rigid Bodies – Case Studies and Validation

Steffen Mattern, Gunther Blankenhorn, K. Schweizerhof
Universität Karlsruhe, Institut für Mechanik

2007

Institut für Mechanik
Kaiserstr. 12, Geb. 20.30
76128 Karlsruhe
Tel.: +49 (0) 721/ 608-2071
Fax: +49 (0) 721/ 608-7990
E-Mail: ifm@uni-karlsruhe.de
www.ifm.uni-karlsruhe.de

NUMERICAL SIMULATION OF CONTROLLED BUILDING COLLAPSE WITH FINITE ELEMENTS AND RIGID BODIES – CASE STUDIES AND VALIDATION

Steffen Mattern[1], **Gunther Blankenhorn**[1] **and Karl Schweizerhof**[1]

[1]Institut für Mechanik
Universität Karlsruhe (TH)
Englerstrasse 2, D-76131 Karlsruhe
e-mail: steffen.mattern@ifm.uni-karlsruhe.de

Keywords: building collapse, finite elements, rigid bodies

Abstract. *In this contribution numerical analyses are presented in order to predict the collapse of buildings subjected to controlled explosives. Global finite element simulations allow the detection of zones with accumulated damage and structural parts with rigid body like behavior. Combined simulations with flexible finite element part and rigid bodies are compared with the validated FE-analysis. The validation is accomplished by a visual comparison of the numerical results to video sequences of the real collapse event. These investigations are performed within the research unit FOR 500 "Computer aided destruction of complex structures using controlled explosives" funded by the Deutsche Forschungsgemeinschaft (German Research Foundation).*

1 INTRODUCTION

At the end of its use and/or lifespan, often the most efficient way of a systematic destruction of a building is to use controlled explosives. Planning such a building destruction, the knowledge about geometry, building materials, the design of the load carrying system and documentation of the original structural analysis is often incomplete and imprecise. However, the boundary conditions such as neighboring buildings or traffic loaded streets require an accurate prediction of the collapse kinematics. Thus, for the preparation of such a collapse event, it is desirable to have a reliable simulation of the complete collapse process, considering the sequence of the blast process and the uncertainty of primary parameters influencing e.g. the resistance of structural elements of a building. The development of a special simulation concept which subdivides the analysis of the collapse mechanism into several problem specific analyses is the central aspect of the project of the 'Research Unit 500' [3], funded by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG).

One subproject of the research unit, located at the University Karlsruhe (TH) is concerned with the generation of finite element models of the entire buildings in order to simulate the complete collapse process as accurately as necessary and carry out a validation with the available documentation data. In addition, on the basis of these finite element simulations, structural parts which fulfill special criteria for rigidity are substituted with real rigid bodies in order to investigate the influence on the kinematics. Detailed information about the position and dimension of such rigid parts is necessary for the development of a special multi-body-system, containing only rigid bodies and hinges represented by nonlinear springs, which allows fairly efficient simulations for the application of fuzzy algorithms in order to consider uncertainties [4].

The contribution describes in detail the investigations on one real building, chosen as a reference structure. The partially simplified global discretization is simulated with explicit finite element analysis using LS-DYNA® [1, 2], in order to reach a reliable simulation of the global collapse kinematics. Parametrical studies were performed regarding material parameters, failure criteria, blasting strategy, etc. Further a criterion for 'rigidity' of structural parts is discussed and according simulations of so-called *hybrid rigid body models* – combined systems of rigid bodies and finite elements – are presented. As documentation of the real collapse process, one rather poor quality video sequence is existing. A visual validation of the simulations is reached via a superposition of the frames of the video and the visualized results of the simulation at particular points in time during the collapse.

2 INVESTIGATED STRUCTURE

As a real world example for the blast simulation, a real storehouse in Weida (Free State of Thuringa/ Germany) has been chosen which has been deconstructed by blast in 1998 (figure 1). The structural system is a seven storey reinforced concrete frame structure with stiffening brickwork outer walls in the first floor and thin concrete walls in the upper floors. The building height as well as length is $22\,\mathrm{m}$, the width is $12\,\mathrm{m}$, which leads to an approximate overall mass of about $1900\,\mathrm{tons}$. The collapse of the building has been achieved in two steps. In a first explosion, two rows of columns in the ground floor have been removed, after four seconds by a second explosion, a third row in the ground floor has been deleted as depicted in figure 2. The weakening, caused by the first explosion was not sufficient to induce the collapse of the building, so the structure remained staying for four seconds on two rows of columns. Only after the destruction of further columns by a second explosion, the building started bending forward, and finally collapsed. First, the complete upper six storeys rotated, then the cuboid approached the ground

Figure 1: Reference structure in Weida/ Germany

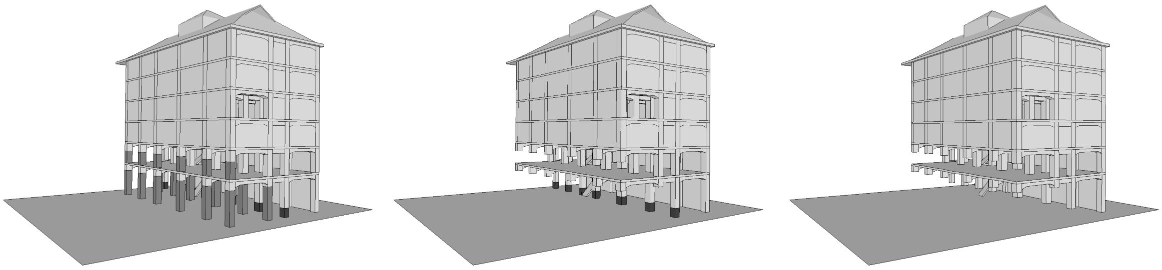


Figure 2: Visualization of the applied blasting strategy

and started to break into pieces.

3 FINITE ELEMENT MODEL

Based on a 3-D CAD-model, generated from the few existing technical drawings, the structure was discretized with altogether 85000 fully under-integrated hexahedral finite elements. This led to an average element size of $20\,\mathrm{cm}$, while a roughly cubic shape was aimed for all elements. This extremely well performing element formulation does not show any locking; however stabilization against unphysical kinematics, the so-called hourglass modes is necessary, for which the assumed strain co-rotational stiffness form by Belytschko/ Bindemann [5] was chosen as implemented in LS-DYNA$^{®}$ [1, 2].

The material behavior was simplified with a homogeneous piecewise linear plasticity model with a failure criterion for maximum plastic strain. The formulation is certainly not able to reproduce the complex behavior of reinforced concrete on local level, but it already led to reasonable results for previous investigations on less complex systems concerning the global kinematics [6]. The models presented in this contribution have the goal to give significant information about the global collapse kinematics of the structure, while detailed local effects are investigated in another subproject within the research unit 500 [3]. Material failure was simulated by element erosion, thus whenever an element reaches the critical value, i.e.

$$\varepsilon_{pl} \geq \varepsilon_{pl,crit} \tag{1}$$

it is completely deleted from the computation. This criterion enables a definite development of local zones with accumulated damage. However, we have to note that the simple application does not allow to distinguish between the failure modes and restricts the investigations to the beginning kinematics of the collapse. In the end of the simulation, the kinematics are dominated by the influence of debris in the lower part of the building, which can not be modelled with the assumptions of element erosion. Therefore, alternative assumptions are currently developed within the project (see also section 4.2, but will not be topic of the present contribution.

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 that an influence of the shockwave resulting from the explosion is found only rather locally and can be consequently neglected in the coarse global investigations. Local effects concerning wave propagation are investigated in another project of the research unit. The global collapse kinematics are characterized by innumerable contacts, occurring during the simulation within the building, as well as between structural parts and the ground plate. The latter is modeled by four-node shell with rigid material behavior, so that deformations of the ground due to impact of structural parts is neglected. elements. Because of the unpredictability of the contact's location, they are all captured, using an automatic segment-to-segment based penalty formulation. As the contact searching algorithm, even if implemented very efficiently is time consuming at this model size, it required a reasonable part – at this model up to $40\,\%$ – of the entire CPU-time necessary for the computation.

4 NUMERICAL STUDIES

4.1 General Informations

In order to achieve a reliable prediction for the location of zones with high damage and the global kinematics, extensive parametrical studies were carried out. The validation with the available video sequence is described in detail in section 5. All simulations were performed on eight parallel processors of the Intel® Ithanium® 2-based *HP-XC6000* Cluster at the University Karlsruhe (TH), using the parallelized MPP-Version of LS-DYNA®. The average turnaround time for the finite element simulation of one single complete collapse of $9\,\mathrm{s}$ duration in reality requires approximately $18\,\mathrm{h}$ compute time on the cluster.

4.2 Pure Finite Element simulation

The simulation of the collapse with a pure finite element model as described in section 3 captures very well the behavior of the building after the first, and the beginning of the kinematics after the second explosion. Figure 4 shows the simulation results at the same time as the snapshots from the video sequence given in figure 3. An approach for a visual validation of the simulation results with the poor quality video sequence is given in Section 5.

Figure 4 shows states of the collapse, before the mass-dominant part of the structure gets into contact with the ground. After this point, a fairly large part of the structure 'disappears' from the computation caused by element erosion, which has a considerable effect on the following kinematics. On one hand, the material in this contact zone fails concerning structural stiffness and strength; on the other hand the resulting debris – removed by erosion in the simulation – in reality still shows resistance against pressure and therefore has influence on the building motion. Consequently, the presented finite element model is not suited for simulating the end of the kinematics, but leads to a good approximation of the beginning. An alternative approach for material failure is e.g. the introduction of detachable nodal connections between the solid elements instead of element deletion. Elements then separate when a specific tension criterion is reached while compression e.g. leads to deformation and compaction of the material. This

Figure 3: Snapshots from the video sequence at times $t_1 = 0\,\mathrm{s}$, $t_2 = 4.4\,\mathrm{s}$, $t_3 = 4.8\,\mathrm{s}$, $t_4 = 5.2\,\mathrm{s}$

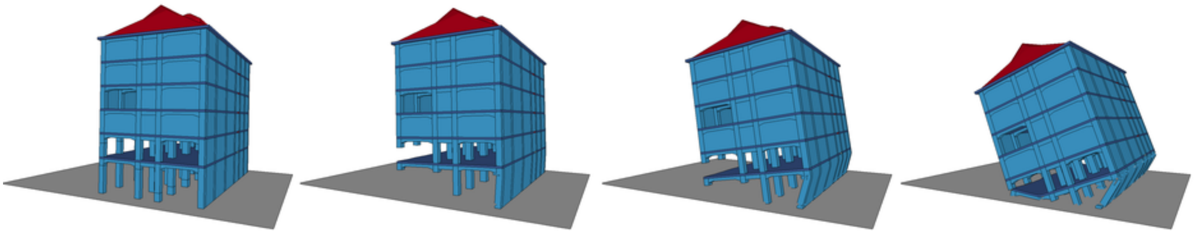


Figure 4: Visualization of the FE-simulation results at $t_1 = 0\,\mathrm{s}$, $t_2 = 4.4\,\mathrm{s}$, $t_3 = 4.8\,\mathrm{s}$, $t_4 = 5.2\,\mathrm{s}$

will certainly lead to a more accurate simulation of the debris behavior within the collapse, which is crucial for the global kinematics especially in the end of the collapse. However, the application of such more complex structural models as well as more precise material models raises the modeling and simulating effort of the analyses which was beyond the available resources in the project. As for the investigation of the research unit the localization of zones with high damage is demanded, the level of accuracy concerning the presented finite element simulations is sufficient as known from former simulations. Further investigations considering higher modeling accuracy are currently part of the work within the project, but can not yet be presented within this contribution.

4.3 Detection of zones with accumulated damage

Based on the finite element simulations from section 4.2, several parts of the model which show fairly small deformations, compared to the local zones of accumulated damage during the whole simulation, can be modeled as rigid bodies in order to reduce the numerical effort and give a basis for an MBS model. As a criterion for rigidity of a body, the strain rate in the flexible parts of the finite element structure is chosen, following the proposal of [8], where

$$\dot{\varepsilon} \leq \dot{\varepsilon}_{crit} \tag{2}$$

defines a structural component as rigid. Parts which do not exceed the value $\dot{\varepsilon}_{crit}$ could be treated as rigid for the full simulation time, the rest of the structure is still modeled with finite elements as described in section 4.2. Figure 5 shows plots of the mean strain-strainrate of a part of the structure at the times $t_2 = 4.4\,\mathrm{s}$, $t_3 = 4.8\,\mathrm{s}$, $t_4 = 5.2\,\mathrm{s}$, according to the states given in the figures 3 and 4. Here green regions represent low and red and blue regions indicate high strainrates. These results lead to a so called *hybrid rigid body model*, where the structural parts fulfilling the criterion are set to rigid by a visual evaluation.

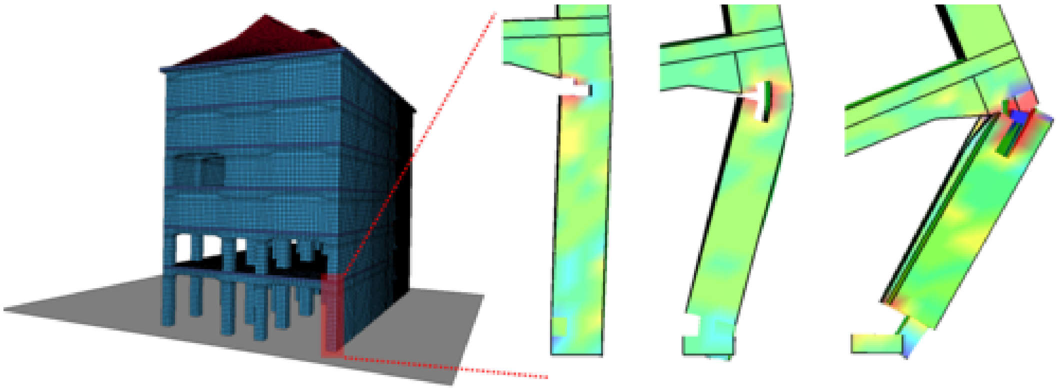
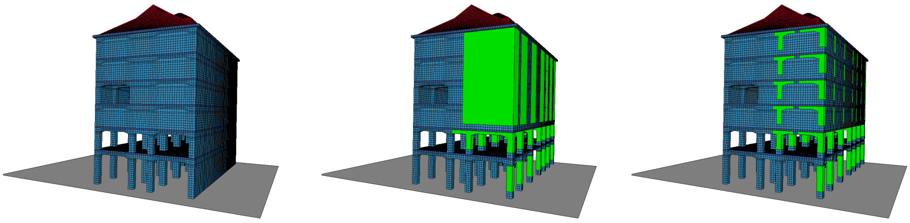


Figure 5: Visualization of the strainrates for the marked zone at the times $t_2 = 4.4\,\text{s}$, $t_3 = 4.8\,\text{s}$, $t_4 = 5.2\,\text{s}$



(a) pure finite element model (b) two different hybrid rigid body models

Figure 6: Hybrid rigid body models on the basis of a finite element discretization

4.4 Hybrid rigid body model

In order to show the influence of rigid bodies on the collapse kinematics in the simulation, flexible parts which show rigid body like behavior regarding the criterion in section 4.3 are substituted by real rigid bodies. The rest of the structure is modeled with finite elements as described in section 4.2. This leads to a model of rigid bodies and finite elements, two examples are shown in figure 6(b). The introduction of real rigid bodies allows a considerable reduction of necessary CPU-time, e.g. the model in the right part of figure 6(b) requires about $60\,\%$ of processing time compared to the pure FE-simulation in Figure 6(a). This shows the benefit of modeling building collapse only with rigid bodies connected by nonlinear hinges, which is a main interest of the research unit. Applying this kind of reduced efficient models allows to perform the high amount of parametrical studies e.g. in order to investigate uncertainties, which is the interest of another subproject of FOR500 [4].

In order to investigate the general influence of rigid bodies on the collapse simulation, analyses on these hybrid models on the basis of validated FE-simulations are performed. Figure 7 shows a superposition of the FE-simulation and the results of the model given in the right part of figure 6(b). It can be seen, that an introduction of rigid bodies in zones, where the structure shows very small deformation has little influence on the beginning kinematics. As the two simulations differ in the last state given in figure 7, the model has to be improved, e.g. by closer investigations of the strain rates or the introduction of further criteria for rigidity. In a next step, additional rigid bodies can be introduced in the upper part of the structure, while the flexible zones are getting smaller. With this procedure, a possible discretization only with rigid bodies, connected by nonlinear springs can be proposed.

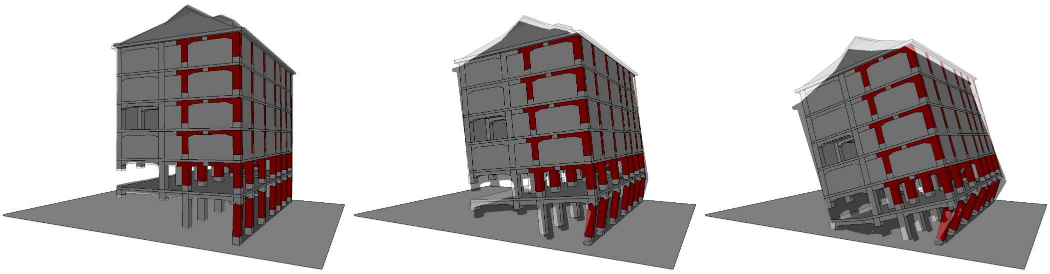
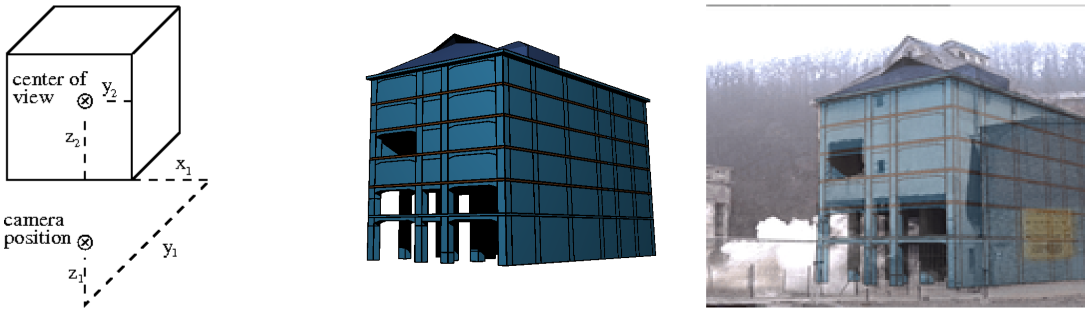


Figure 7: Superposition of pure finite element model (black) and hybrid rigid body model (white and red) at times $t_2 = 4.4\,\mathrm{s}$, $t_3 = 4.8\,\mathrm{s}$, $t_4 = 5.2\,\mathrm{s}$



(a) camera position (b) visualization of results (c) superposition

Figure 8: Procedure for the superposition of the simulation data with the video sequence

5 VALIDATION WITH VIDEO SEQUENCE

As already mentioned, the investigated reference structure, presented in this contribution was deconstructed in 1998, which makes it difficult to get documentative data for the building. The documentation of the collapse is limited to one video sequence, provided by the engineering company, which was responsible for the blasting demolition. The sequence was recorded with a standard camcorder for reasons of private documentation. Consequently, the video contains no measuring points, so it is only usable for a visual validation. This requires information about position and perspective of the camera, in order to create a visualization of the simulation results with the same configuration. The camera position and its angle has been reconstructed by a graphical procedure on basis of the photography of the building, given in figure 1. The results are shown in figure 8(a).

After that a 3-D-scenario in the form of a VRML-File is created from the simulation, with help of a post-processing software. This file can be converted as an input for the rendering software *Povray*, which is used to render the 3-D-scenario with user-defined information about the position and perspective of the camera. This leads to a picture of the state of the simulation, which matches the according state from the video sequence. Finally the state of the simulation and the snapshot from the video sequence are superposed using a graphics software, which allows a qualitative validation of the analysis. For the reference structure, presented in this contribution, this procedure is depicted in figure 8.

As figure 9 shows, the results of the performed FE-simulation shows very good correlation to the video sequence. Consequently, the position of rigid bodies and zones of accumulated damage for the beginning kinematics can be reliably obtained from the presented FE-simulation.

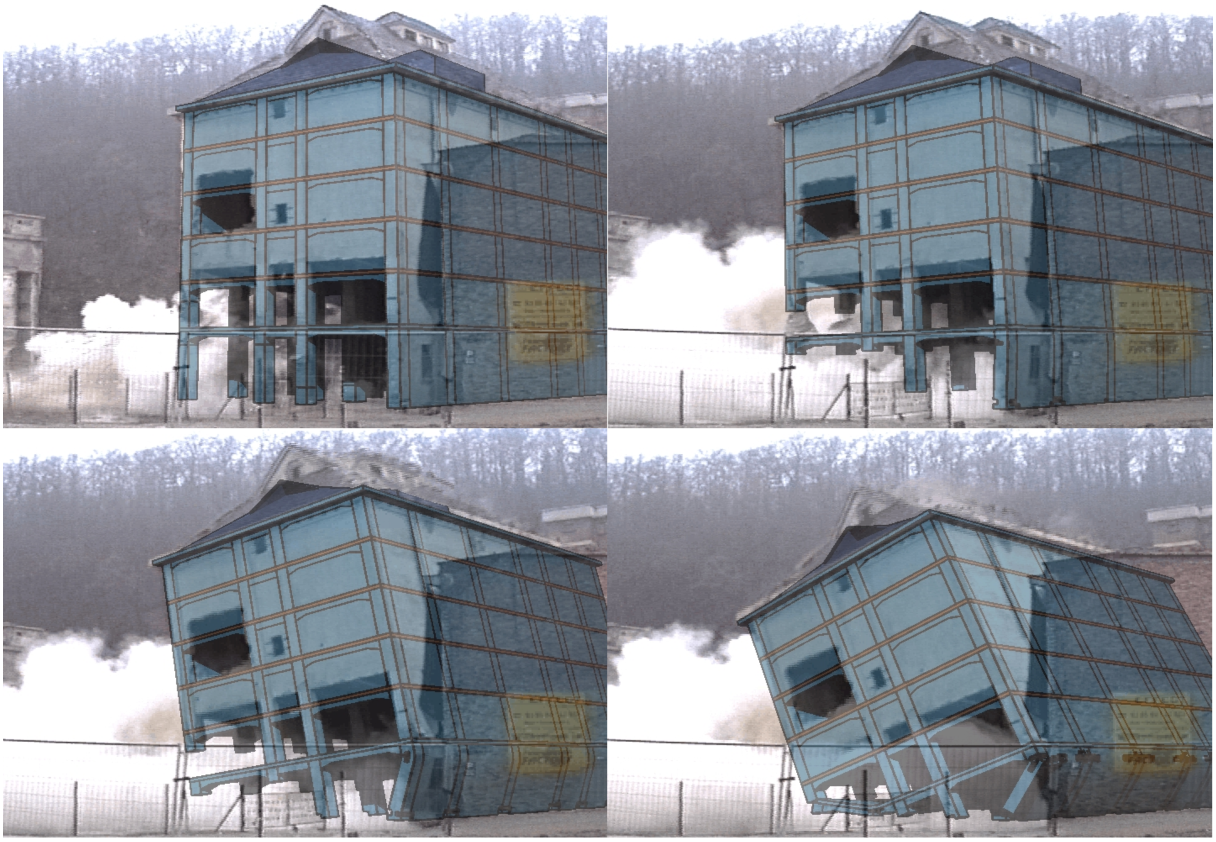


Figure 9: Video sequence and FE-simulation at times $t_1 = 0\,\mathrm{s}$, $t_2 = 4.4\,\mathrm{s}$, $t_3 = 4.8\,\mathrm{s}$, $t_4 = 5.2\,\mathrm{s}$

The validation of the finite element analyses is also important for the further work of the research unit, as a verification of the simulation with pure rigid body models can be achieved with this validated FE-analysis.

6 CONCLUSION AND OUTLOOK

Within this contribution, the general possibilities of modeling building collapse initiated by controlled explosion with explicit finite element analysis are discussed. It has been shown, that the beginning of a building collapse, described by a few rigid body like parts, connected by local zones of accumulated damage is very well captured by the presented finite element model. In the course of the collapse process, due to the increase of complexity of the kinematical system, the simulation results differ cumulatively, caused by the rather simplified description of the complex material behavior of reinforced concrete. In the presented case, especially the modeling of material failure by element erosion at specific criteria is mainly responsible for the unphysical change in kinematics, because in reality, debris has still influence on the structure, which can not be modeled by the presented simulation approach. Further investigations with more suitable structural and material models and the development of better fitting failure criteria for reinforced concrete are currently investigated. The possibility of replacing structural parts which do not show large deformation during the whole collapse by rigid bodies is discussed. Information about the dimension of the rigid parts and the location of flexible connections can be obtained by special criteria. In this contribution, strain-rates were analyzed, a closer view at e.g. plastic strains or stresses can help to improve the hybrid rigid body model. Within the research unit, these investigations are meant to develop generalized rules in the form of structural subsystems of rigid bodies connected by nonlinear hinges in order to simulate the building collapse.

In order to judge the quality of the finite element solution, which is necessary to accurately identify the rigid zones, it is important to realize a validation of the analyses. For this reason, the few documentation of the collapse of the chosen reference structure was used to carry out a visual validation by superposing the simulation results with the video sequence. The presented finite element simulations and the investigations on the buildings reaction when structural parts are substituted by rigid bodies are very important for the development of efficient and reliable building collapse prediction within the research unit.

7 ACKNOWLEDGEMENTS

The presented photographs as well as all necessary information about the reference structure in Weida are due to courtesy of Dr.-Ing. Rainer Melzer, Planungsbüro für Bauwerksabbruch, Dresden.

The financial support of the German Research Foundation (DFG) (Project DFG-FOR 500 – 'Computer aided destruction of complex structures using controlled explosives') is gratefully acknowledged.

REFERENCES

[1] J.O. Hallquist, *LS-DYNA Theory Manual*. Livermore Software Technology Corporation, 2006.

[2] J.O. Hallquist, *LS-DYNA Keyword User's Manual*. Livermore Software Technology Corporation, 2007.

[3] DFG Research Unit FOR500, *http://www.sprengen.net*. 2007.

[4] B. Möller and M. Beer, *Uncertainty in Civil Engineering and Computational Mechanics*. Springer, Berlin, 2004.

[5] T. Belytschko and T.B Bindemann, Assumed strain stabilization of the eight node hexahedral element. *Computer Methods in Applied Mechanical Engineering*, **105**, 225–260, 1993.

[6] S. Mattern, G. Blankenhorn, M. Breidt, V. Nguyen, S. Höhler, K. Schweizerhof, D. Hartmann and F. Stangenberg, Comparison of Building Collapse Simulation Results from Finite Element and Rigid Body Models. *Proceedings of IUTAM Symposium on Multiscale Problems in Multibody System Contacts*, Stuttgart, 2006 (in press).

[7] Scientific Supercomputing Center of the University Karlsruhe, *http://www.rz.uni-karlsruhe.de/ssck*.2007

[8] B. Göttlicher, *Effiziente Finite-Element-Modellierung gekoppelter starrer und flexibler Strukturbereiche bei transienten Einwirkungen.*. Universität Karlsruhe (TH), Institut für Mechanik, 2002.