Numerical Investigation on Collapse Kinematics of a Reinforced Concrete Structure within a Blasting Process

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Abstract:

In the present contribution numerical analyses were performed in order reach a prediction of the collapse kinematics of a real building subjected to blast loading. The collapse process is simulated with a pure finite element model and "validated" by a video sequence of the blasting process. A criterion for substituting several structural parts with rigid bodies is discussed and the resulting simulations are compared with the pure finite element solution. All finite element and so called 'hybrid rigid body' simulations were performed with the parallelized version of LS-DYNA on the HP-XC6000 Cluster at the University of Karlsruhe. These investigations are processed within the research unit FOR 500 *"Computer aided destruction of complex structures using controlled explosives"* funded by the Deutsche Forschungsgemeinschaft (German Research Foundation).

Keywords:

building collapse, element erosion, rigid bodies,

1 Introduction

At the end of its use and/or lifespan, often the most efficient way of a purposeful 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 collapse, considering 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 work of the '*Research Unit 500*' [8], funded by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG). One subproject of the research unit, located at the University of Karlsruhe (TH) is concerned with the generation of finite element models of the complete 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 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 [7].

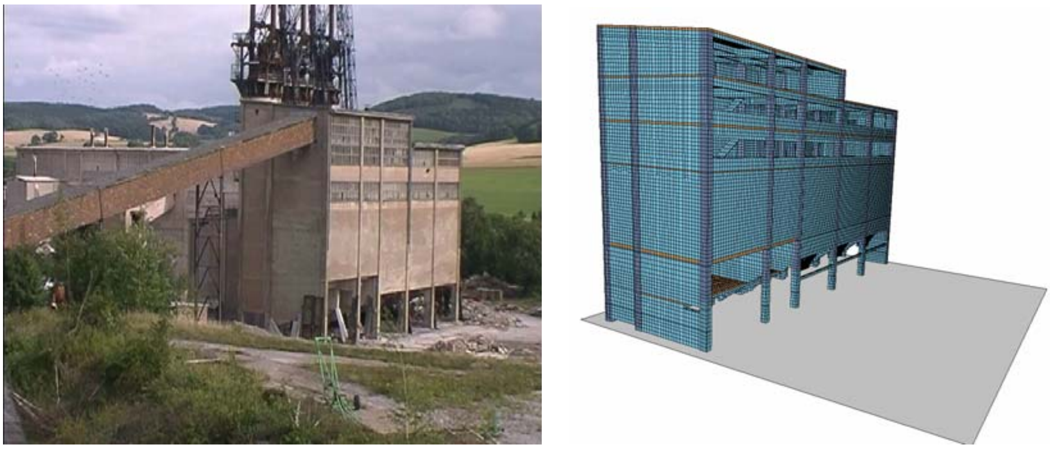
The present contribution describes in detail one investigated reference structure and its simulation with explicit finite element analysis using LS-DYNA. Further a criterion for "rigidity" of structural parts is discussed and according simulations of so called hybrid rigid body models – combined systems of rigid bodies and finite elements – are presented.

2 Investigated structure

The chosen reference structure is an industrial building in the form of a silo structure, originally belonging to the lime works in Borna/ Sachsen in Germany. The destruction with controlled explosives was carried out in April 2000 by the engineering company 'Planungsbüro für Bauwerksabbruch – Dr.-Ing. Rainer Melzer'. 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 collecting bins inside the building are of reinforced concrete, the outer walls of masonry. The mass of the building, including all structural parts is estimated to approximately *3630 tons*. The collapse, in the form of tipping over was achieved by removing the front side columns by controlled blast. In order to make sure that the kinematics starts correctly after the explosion which is applied in a certain sequence, the back side columns were additionally weakened by cutting parts of the reinforcement. Also parts of the inner thin concrete walls, which stiffen the structure, were removed before by standard demolition techniques. Figure 1(a) shows a photograph of the investigated structure, directly before the explosion. A view of the discretized structure is given in Figure 1(b). Snapshots of a video sequence of the building collapse at different time states are shown in Figure 2.

3 Finite Element model

Based on a 3-D CAD-model, generated from the existing static analysis and technical drawings, the structure was discretized with altogether 77079 fully under-integrated hexahedral finite elements (LS-DYNA element type 1). This led to an average element size of *30 cm*, while a roughly cubic shape was aimed for all elements. The 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 [1] was chosen (LS-DYNA hourglass control type 6 [3],[4]). The discretization was purposely not further refined yet as will be discussed below.



(a) (b)

Figure 1: *Silo structure in Borna, real structure with other industrial buildings in the background (a) and discretized system (b)*

The material behavior was simplified with a homogeneous piecewise linear plasticity model using LS-DYNA material type 24. 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 a number of previous investigations on less complex systems concerning the global kinematics [5],[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 [8]. Material failure was simulated by element erosion at a specific plastic strain which can be defined within the applied material formulation [3],[4]. Thus whenever an element reaches this critical value, i.e.

$$\varepsilon_{pl} \geq \varepsilon_{pl,crit} \qquad (1)$$

it is removed from the computation. This criterion enables a definite development of local zones with accumulated damage. The location of such zones is necessary for the generation of the multi-body systems mentioned in Section 1. However, we have to note that the simple application does not allow to distinguish between the failure modes.

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 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 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. As the contact searching algorithm, even if implemented very efficiently is time consuming at this model size, it required a reasonable part – up to 60 - 80 % – of the entire CPU-time necessary for the computation.

The Finite Element model which is depicted in Figure 1(b) represents a rather coarse simplification of the real building which is not supposed to reproduce the real collapse in every detail. Nevertheless a good approximation of the global kinematics as well as the detection of local zones with accumulated damage can be achieved already with this level of modeling accuracy.

4 Numerical studies

4.1 General Information

In order to achieve a reliable prediction for the location of zones with high damage and the global kinematics, several parametrical studies were carried out and compared to a video sequence of the collapse. Unfortunately, this sequence – different states are depicted in Figure 2 – is the only data available for some kind of validation. All simulations were performed on eight parallel processors on the

HP-XC6000 Cluster at the University of Karlsruhe (TH), using the parallelized MPP-Version of LS-DYNA.

4.2 Pure Finite Element simulation

The simulation of 8 seconds with the pure finite element model as described in section 3 – the time, the complete collapse lasted in reality – required *1.047* 10^5 *s* (*29 h 4 min 36 s*) on the computing environment described in Section 4.1. The simulation captures very well the combination of vertical translation and rotation in the beginning of the collapse, which turns into a pure rotation at a certain point. Figure 3 shows the simulation results at the same time as the video snapshots in Figure 2. After the hoppers get into contact with the ground plate, the erosion of the elements appears to lead to wrong results. A fairly large part of the lower structure "disappears" from the computation, which has a considerable effect on the following kinematics. On one hand, the material of the hoppers fails concerning structural stiffness and strength; on the other hand the resulting debris – removed by erosion in the simulation – in reality still has influence on the building motion. Especially at the end of the collapse, given in Figure 4, a certain disagreement of real process and simulation is visible, caused by an unphysical "loss" of material by element erosion during the computation. Figure 5 points out that more than 60 % of the hopper's material erodes during the collapse, which seems to have important influence on the kinematics. However, regarding the results in Figure 3 and Figure 4, at the beginning of the process the kinematics can be captured very well with the simplified finite element model.

Figure 2: *Video sequence at different time states (0.0 s – 1.8 s – 3.0 s – 4.8 s)*

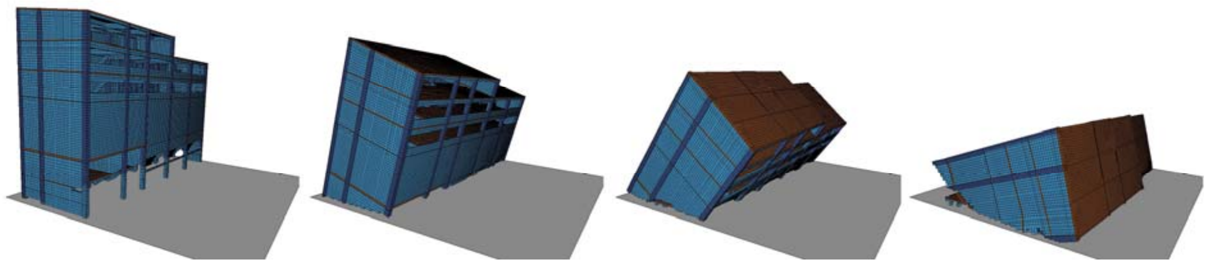


Figure 3: *Pure Finite Element simulation at different time states (0.0 s – 1.8 s – 3.0 s – 4.8 s)*

At this point, we want to stress again, that a major goal within the research unit is a simple failure model to allow a proper judgment of the global destruction process. Further investigations on finer discretizations using more accurate material models would certainly lead to closer approximations of the real collapse kinematics with the pure finite element simulation. 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 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 current state of 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 will follow in the near future.

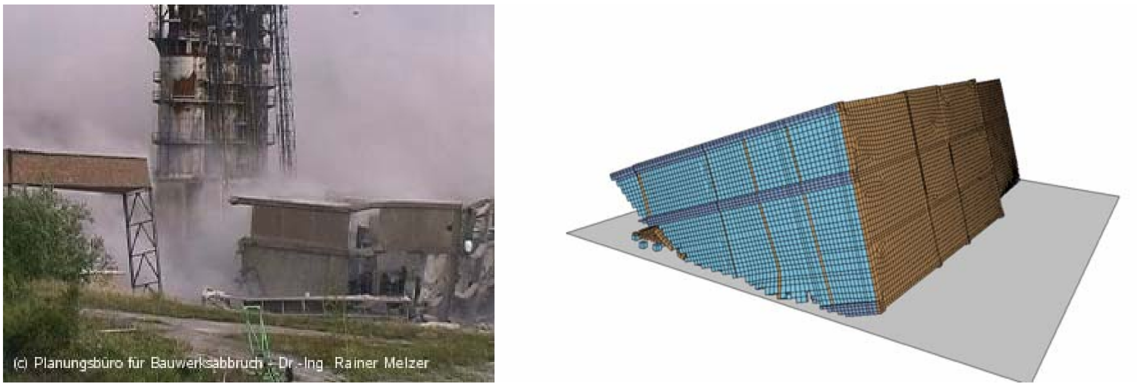
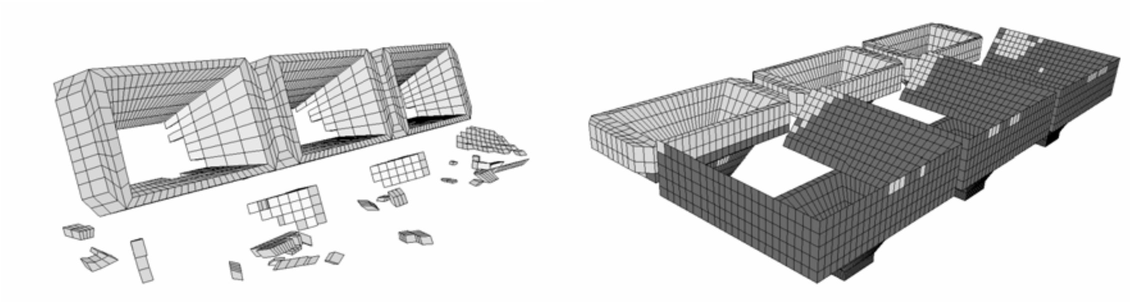


Figure 4: *Video and simulation at the end of the collapse (t = 8.0 s)*



(a) (b)

Figure 5: *Erosion of hoppers after collapse (a), dark elements erode during collapse (b)*

4.3 Detection of local zones with accumulated damage

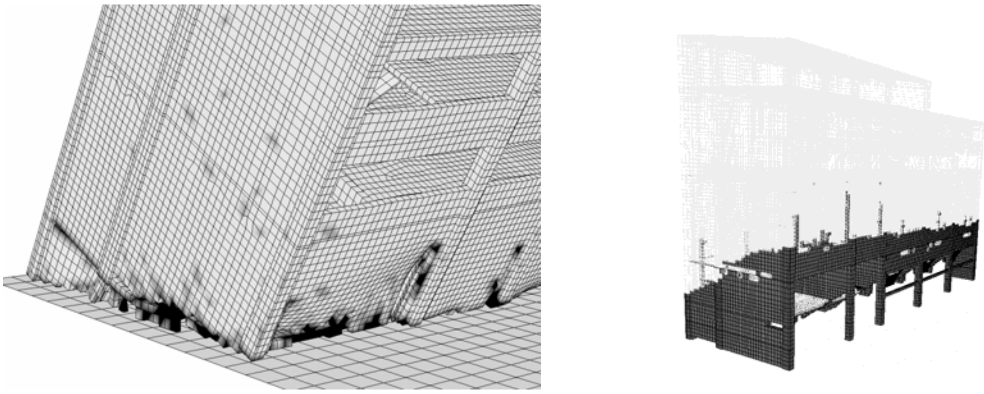
Based on the finite element simulations from Section 4.2, several parts of the model which show fairly small deformations, compared to the local zones of accumulated damage during the whole simulation, are modeled now as rigid bodies to reduce the numerical effort and to give a basis for an MBS model. As criterion for rigidity of a body, the strain rate in the flexible parts of the finite element structure is chosen, following the proposal of [2], where

$$\dot{\varepsilon} \leq \dot{\varepsilon}_{crit} \quad (2)$$

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 6(a) shows a plot of the mean strain-strainrate at time 2.4 s where dark regions represent high strainrates. This corresponds well with Figure 6(b), where all elements eroded already at that time are shaded dark. The results of the investigations based on the fully finite element model given in Figure 1(b) lead to a so called *'hybrid rigid body model'*, where the structural parts fulfilling the criterion where set to rigid.

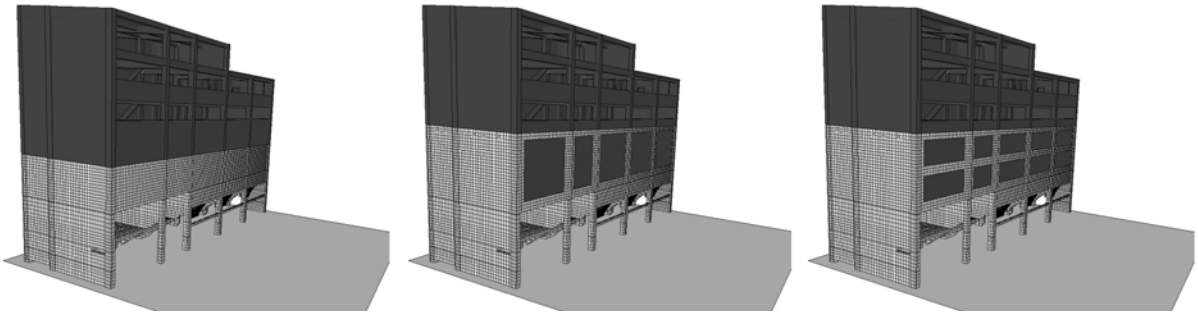
4.4 'Hybrid Rigid-Body-Model'

In order to show the influence of substituting the flexible parts which can be assumed to be rigid with real rigid bodies, three simulations carried out with LS-DYNA are presented. Based on the finite element model from Section 4.2 and the investigations presented in Section 4.3, rigid bodies were introduced into the reference structure. Figure 7 shows three hybrid rigid body discretizations with different numbers of independent rigid bodies, where all models consist of approximately 50 % rigid bodies and 50 % finite elements. Further information about the presented discretizations and the simulations are given in Table 1. A comparison of the simulation results of all three model is depicted in Figure 8.



(a) *(b)*

Figure 6: *Cutout of strainrate plot with high strainrates in dark parts (a) and dark shaded elements (b) eroded at time t = 2.4 s in the pure finite element simulation*

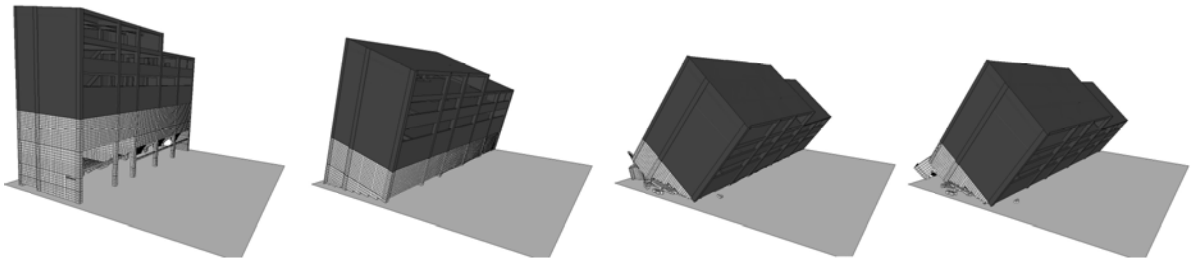


(a) *(b)* *(c)*

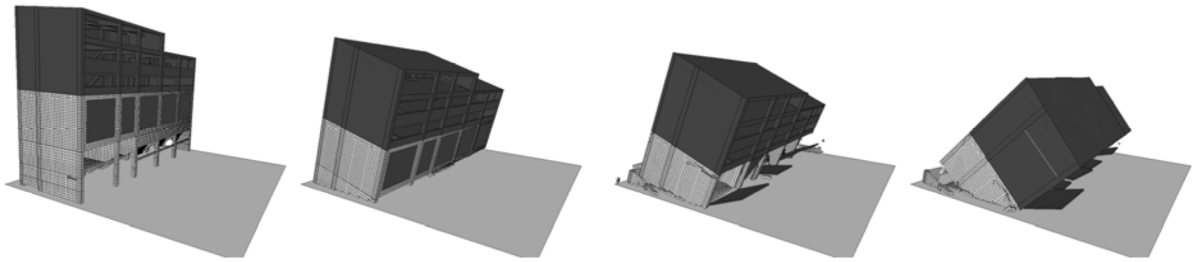
Figure 7: *Different hybrid rigid body models – combined discretizations containing finite element parts (bright) and rigid body parts (dark). Strongly simplified model with only one rigid body (a), first subdivision (b) with 16 and second (c) with 29 independent rigid bodies.*

model	finite elements	rigid bodies	number of rigid bodies	processing time
(a)	*49.7 %*	*50.3 %*	1	*9 h 37 min 5 sec*
(b)	*48.5 %*	*51.5 %*	16	*5 h 28 min 13 sec*
(c)	*49.6 %*	*50.4 %*	29	*11 h 14 min 31 sec*

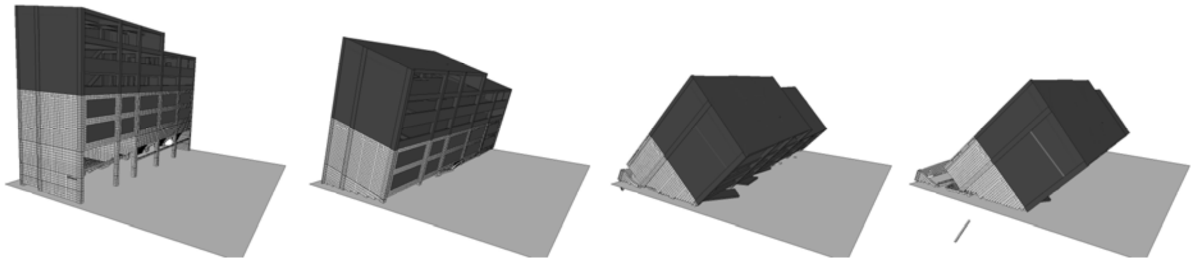
Table 1: *Summary of the different hybrid rigid body models*



(a)



(b)



(c)

Figure 8: *Simulation results of the investigated hybrid rigid body models described in Table 1 at different time states (0.0 s – 1.8 s – 3.0 s – 4.8 s)*

The first, strongly simplified model from Figure 7(a) contains only one rigid body, which represents the entire upper part of the building. In the first part of the collapse, the model shows rather good correlation with the pure finite element model, while after the rigid body is getting into contact with the ground plate, the kinematics change dramatically. Consequently, the discretization is oversimplified to resemble the finite element solution and a refinement of the rigid bodies is required to obtain better correlation.

In the second investigated hybrid rigid body model proposed in Figure 7(b), the size of the upper rigid body was reduced and additional separate rigid bodies were introduced in the inner parts of the walls, parallel to the longer side of the building. The rigid parts are connected by parts discretized with finite elements, which are modeled with the material parameters from the pure finite element model. As shown in Figure 6(a), high strainrates appear mainly at the connection of walls and columns while the inner regions of the walls remain rather undeformed. Also element erosion is recognized along the columns as can be seen in Figure 6(b). In addition, parts of the collecting bins were modeled with rigid bodies. Altogether the model consists of 16 independent bodies connected by finite element meshes. As expected in Figure 8(b) a better correlation to the original simulation than with the first more simplified assumption is found.

A rather unphysical behavior in the course of the collapse is caused by the modeling of the walls with only one rigid body. Consequently a subdivision of the rigid bodies by introducing further local finite element parts, leads to the third investigated hybrid rigid body model presented in Figure 7(c). Here two bodies, connected by a row of finite elements were used to model each wall. The kinematics of the pure finite element simulation can be captured even better with this still heavily simplified approximation.

A closer view on the strainrate distribution in different parts of the finite element model may certainly lead to further subdivisions of the rigid bodies. The results in Figure 8(b) and Figure 8(c) anyhow show e.g. that the modeling of the collecting bins requires finer subdivision of the rigid bodies as the kinematics of the chosen structure changes in the end of the collapse. However, it can be realized from the results that a combined simulation with rigid and deformable parts can lead to an acceptable accordance with the pure finite element solution.

Concerning the processing time of the hybrid rigid body models given in Table 1, a considerable reduction is achieved compared to the pure finite element model. The presented systems required about 60 - 80 % less CPU-time on the same computing environment, which is mainly due to the reduction of contact searching effort by merging a group of finite elements into one rigid body. 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 500. Applying this kind of reduced efficient models allows to perform the high amount of parametrical studies e.g. in order to investigate uncertainties.

5 Conclusions and Outlook

Within this contribution, the general possibilities of modeling building collapse initiated by controlled explosion/ blast 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 does not exist in the presented simulation. Further investigations with more suitable structural and material models and the development of better fitting failure criteria for reinforced concrete are fields of further investigations.
Further the combination of rigid bodies and finite elements with LS-DYNA was discussed. Replacing structural parts which do not show large deformation during the whole collapse can reduce the computational effort drastically without having large influence on the kinematical behavior. The idea in the context of the research unit 500 is to develop generalized rules in the form of structural subsystems of rigid bodies connected by nonlinear hinges in order to simulate the building collapse. For this reason, the 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.

6 Acknowledgements

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