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1 Introduction

In case of planning a building demolition, the information about geometry, quality of building materials, the design of the load carrying system and documentation of the structural calculation is often incomplete and imprecise. Thus for the analysis of a collapse event, engineers are forced to consider the uncertainty of primary parameters influencing e. g. the resistance of structural elements of a building. This kind of uncertainty can be described using suitable data models such as fuzziness and fuzzy randomness [6]. Within such an 'uncertain' structural analysis the deterministic fundamental solution is applied repeatedly. A comprehensive overview over algorithms of fuzzy analysis and fuzzy stochastic analysis is given in [5]. First applications of uncertainty collapse analyses can be found in [7, 8]. However, considering several uncertain parameters in an analysis the problem dimension and the necessary effort can be quite high. To receive a good prediction for a complex building collapse, several hundred or even more deterministic solutions are needed. This requires an efficient and fast scheme to perform the analysis

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for highly nonlinear problems, concerning geometry, material and changing boundary conditions such as contact.

In particular, efficient multi rigid body models for the simulation are therefore created, that are supported and validated by finite element methods. The investigation presented in the following shows results and comparisons of building collapse simulation from finite element as well as rigid body models elaborated in a joint research project. The partners in this project are stemming from different institutes (Computational/Structural Mechanics, Reinforced Concrete and Engineering Informatics). A common goal of the joint project is the realistic and efficient deterministic simulation of real-world structures that builds a foundation for continuative studies like the aforementioned fuzzy analysis.

2 Analysis concept

As mentioned in section 1 an efficient analysis is needed to predict the holistic demolition process especially the collapse sequence of a building. Commonly used numerical analysis tools are finite element programs, which allow a very flexible discretization, approximating arbitrary geometries and materials to predict the behavior of real structures under estimated loads and boundary conditions. However, even if highly efficient algorithms and implementations are applied, efficiency problems occur for complex structures concerning the calculation time, e.g. a six storied reinforced concrete building with a simple cubic geometry, discretized with 85000 solid elements, needs several hours for the solution on an eight processor (Intel® Itanium® 2) node of a Linux system. One possibility to reduce the calculation time considerably is to use multibody models instead of finite elements. Such models are highly efficient with respect to the calculation time.

The main problem while using rigid body models is the proper modeling if various contact situations happen during a collapse event or if local zones of accumulated damage appear, which cannot be represented and detected by a rigid body. A solution concept to overcome this problem and to develop an efficient scheme which is used in this investigation includes both, finite element analysis as well as rigid body models. The finite element analysis supports the modeling process of the rigid body model; it also allows to predict the behavior of the local zones of accumulated damage and the region of moderate deformation which can be estimated as rigid. This is also taken to gain experience defining suitable rigid body models. Once the rigid parts are identified, the hinges between the various rigid bodies must be linked to a characteristic resistance curve which represents the resistance against relative rotations or displacements of the individual bodies. To get a good approximation of the behavior of the real structure in zones of local damage, finite element submodels are separately created with a fine discretization and rather sophisticated material models. Via this approach, characteristic resistance curves are produced for some standard load cases which are expected in the collapse event.

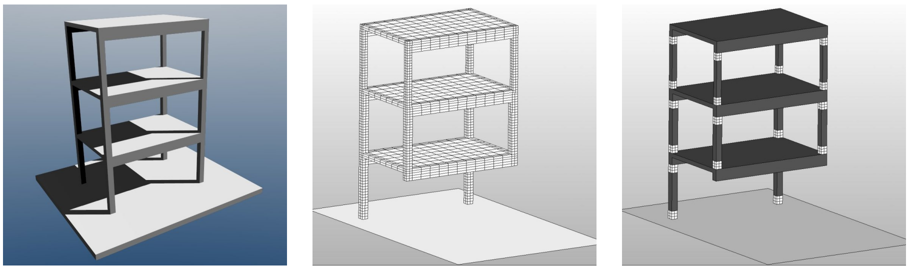
Summarizing the concept, in a first step a finite element analysis is used to support the setup of a special multi rigid body model for efficient simulation of collapses. Thereby, one of the main goals is to develop suitable multibody systems such that parts with moderate deformations can be treated as rigid, defining the different rigid body parts of the multibody system. Then the zones of local damages are identified and modeled using tailored multibody subsystems that are built up with multibody elements using nonlinear force elements according to the characteristic resistance curves. These curves are calculated a-priori by a separate detailed finite element submodel of the structure. The following sections show fundamentals of (i) the global finite element analysis of the entire structure, (ii) the finite element analysis of the local zones of accumulated damage applying specialized material models for dynamically reinforced concrete and (iii) the developed multi body based simulation system.

3 Example description / Fundamentals of applied finite element and multibody models

3.1 Model description / Reference System

In order to compare results within the development of a procedure for the generation of a multi body system (MBS), a selected reference model is used. For simplicity, all investigations presented in this paper are based on a fictitious, three-storied framework structure of reinforced concrete as shown in Figure 1(a).

The destruction of this structure is initialized by removing the two front side columns, which leads to a collapse under dead load. This rather moderately complex reference model was chosen to develop the simulation process in all details, taking advantage of reduced simulation requirements and representing the expected exchange of data between the different simulation concepts. The described simulation process can be later taken in an identical fashion for far more complex building simulations.



(a) Reference geometry (b) FE-discretization with front columns removed (c) Developed 'hybrid rigid body model'

Figure 1: Three story framework – geometry, pure FE-model and hybrid rigid body model – removal of front columns for blasting simulation

3.2 Finite Element model

The geometry in Figure 1(a) has been discretized with 2330 eight-node hexahedral finite elements (Figure 1(b)) and computed with explicit time integration, using a central difference scheme [4, 3]. The rather coarse mesh leads to a fairly good approximation, mainly because of the one-point underintegrated solid elements, which do not show locking. However, for these elements a stabilization against unphysical kinematics, the so-called hourglass modes is necessary, for which the assumed strain co-rotational stiffness form by Belytschko/ Bindemann [3, 4, 1] was chosen. The blasting process was simulated — as mentioned above — by removing the two front side columns at the beginning of the computation. Under dead load, this leads to a certain collapse kinematics with the appearance of hinges, i. e. zones of local accumulated damage, which are modeled with appropriate multibody subsystems e.g. joints combined with nonlinear springs in an MBS-Simulation. In order to detect these local zones in a rough manner, element failure was introduced, here by introducing a critical plastic strain $\varepsilon_{pl,crit}$. Every element, which fulfills the condition

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

at any time of the simulation, is removed (eroded) from the computation. This means, in regions with high plastic strains, many elements erode, which automatically leads to the development of the described local zones. The reinforced concrete has been modeled with a simplified, homogeneous material — *piecewise linear plasticity* — where the parameters concerning plasticity and erosion have been determined by simple experiments.

3.3 Hybrid rigid body model

Based on the Finite Element (FE) simulations from section 3.2, several parts of the model which show 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. As criterion for rigidity of a body, the strain rate in the flexible parts of the FE structure is chosen, following the proposal of [2], 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 3.2. The 'hybrid rigid body model' as a result of the finite element simulation based on the initial fully FE model given in Figure 1(b) is shown in Figure 1(c), where the black parts are rigid bodies and white parts are local finite element meshes.

3.4 Multi rigid body model

Based on the finite element analyses, rigid parts with initially little deformation and parts with larger deformation could be localized. For the multi body analyses a suitable subsystem with similar kinematic and dynamic behavior such as the 'costly' FE model has to be defined to simulate the failure process. As found in the FE simulation, the main failure areas are at the bottom and at the top of the columns (Fig. 2a). For that it is appropriate to model a column as one rigid body with hinges and spring elements on bottom and top (Fig. 2b+ 2c). To correctly achieve the failure characteristics of reinforced concrete, the spring elements are defined by pre-calculated nonlinear characteristic resistance curves.

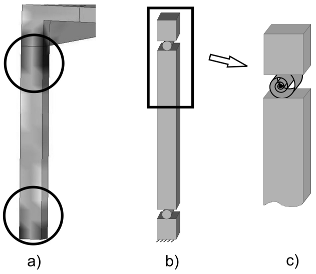


Figure 2: Column modeled as rigid body with hinges and nonlinear spring elements

3.4.1 Determining the characteristic resistance curves

To determine the nonlinear characteristic resistance curves for the spring elements a detailed finite element analysis is applied. Compared to the finite element analyses of the global structure, the size of the elements is rather small, leading to up to 5000 hexahedral elements for one column. In the local zones the stress resultants in a cross section are computed in every step with a stress integration over the area. Also the curvature/rotation according to the different stress resultants are stored. The implemented material model, described in [10] is a 'close-to practice' elastic-plastic damage theory model for reinforced concrete. It is applied to solid and solid-shell elements, used in the analyses.
To describe the behavior of concrete under compression a yield/damage potential of Drucker-Prager-type is taken:

$$\Phi_c(\sigma,\alpha) = \frac{1}{\frac{1}{\sqrt{3}} - \mu} \left[\mu\, I_1 + \sqrt{J_2}\right] - \alpha_c(q_c), \tag{3}$$

where I_1 is the first invariant of the stress tensor σ and J_2 the second deviator invariant. The term left of the brackets guarantees that during plastic loading α_c always corresponds to the negative uniaxial compression stress. For tension, a damage potential of Rankine type is used for all three main stress axes

$$\Phi_{t(i)}(\sigma,\alpha_t) = \xi_i - f_t \le 0, \quad i = 1,2,3. \tag{4}$$

The reinforcement is modeled by truss elements with elasto-plastic behavior. To simplify matters only tension softening is considered. The model is very efficient for uncertainty analyses. The computed characteristic resistance curves are stored in the model database for the multi body system program which will be described in the next section.

3.4.2 Assembling the multi rigid body system

For the multibody simulation, appropriate subsystems are assembled to a special multibody model for the discussed reference system. This is carried out by a simulation platform using information and data generated by the different aforementioned finite element analyses.

In Figure 3, schematically the concept of the simulation model of the platform is depicted. The simulation model is based on different submodels. The submodel a) in Figure 3, represents the product model for a so-called 'demolition using explosives'. This submodel serves as a database and contains all relevant data needed for the global level simulation, such as the position, the geometry and material data of the parts of the building, the

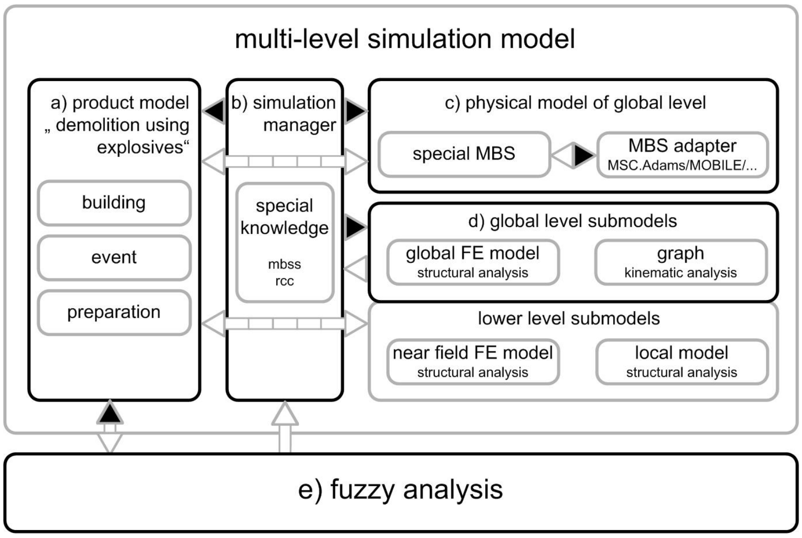


Figure 3: Schematic presentation of the simulation model

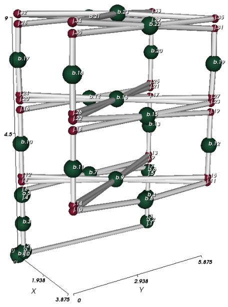


Figure 4: Schematic presentation of the special multibody model showing the kinematic skeleton and the mass properties

details of the preparatory work (modifications of the static structure of the building before ignition of the explosives) and the potential events (locations and ignition times of explosive loads). Using these data along with the results of the different submodels of the global level (d) as well as the lower levels, the submodel 'simulation manager' (b) creates a model description of the special multibody system (c). This modeling process is carried out by using special knowledge gained from the various finite element analyses. The creation and solution of the system equations is accomplished by a multibody system (MBS) software that is applied by the special MBS submodel via a specific MBS adapter (c). Currently, the program system MSC.Adams [9] is applied. The described simulation platform provides interfaces, here, exemplarily shown for the fuzzy analysis [5].

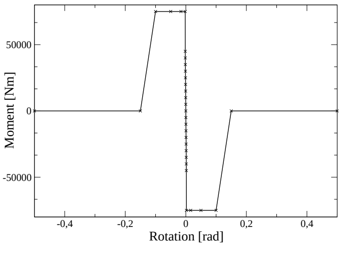


Figure 5: Characteristic resistance curve

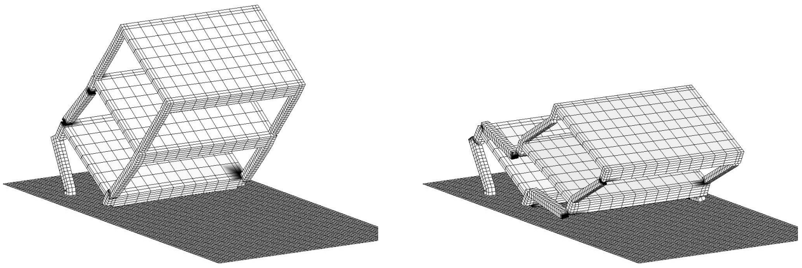


Figure 6: Visualization of the strainrate at two states of the collapse simulation with full FE-model

In Figure 4, the resulting multibody model of the reference system is demonstrated. According to the results of the finite element analyses, all columns are connected to the neighboring structural elements by revolute joints with distinct rotational springs with nonlinear characteristics defined by the characteristic resistance curves. Figure 5 shows exemplarily the characteristic resistance curve for the bottom rotational spring.

4 Numerical Analysis and results

4.1 Finite Element model

In Figure 6, two states of the finite element simulation with a critical strain rate of $\dot{\varepsilon}_{crit} = 0.25$ are shown. The black parts of the structure show strain rates, larger than the critical value, which indicates local zones of accumulated damage. The bright parts show rigid body like behavior, because $\dot{\varepsilon} \leq \dot{\varepsilon}_{crit}$. This investigation of the strain rate over the whole collapse, which is about 2 s, leads to a combined model of rigid bodies and finite elements as shown in Figure 1(c), there labeled as 'hybrid rigid-body model'.

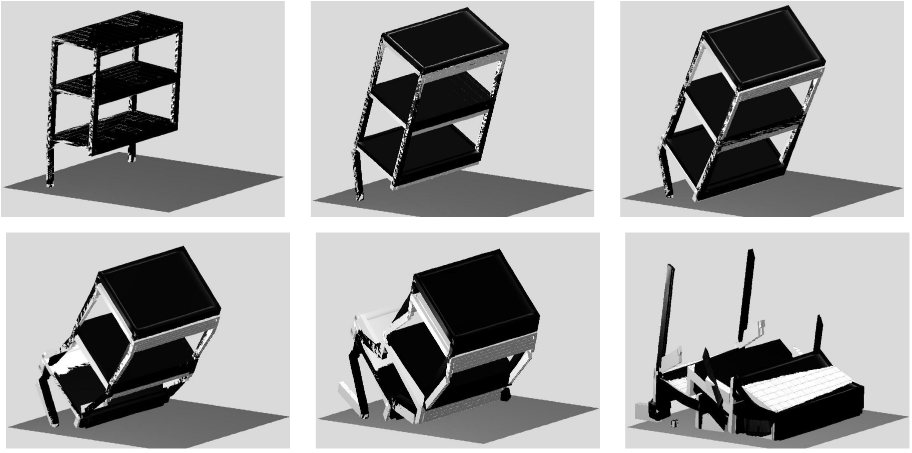


Figure 7: Pure finite element model (black) and hybrid rigid-body model (white) compared at different time states

4.2 Hybrid rigid body model

Both, FE- and hybrid rigid body model, seem to correlate very well especially at the beginning of the collapse, as can be seen in Figure 7. Differences become more visible at the end of the collapse; here the subdivision into smaller rigid bodies would be necessary to obtain better correlation. In further investigations, the influence of contact on the kinematics of the collapse has been investigated. Including obstacles leads to different kinematics, different strain rates and consequently to a different hybrid rigid body model. This is implied in Figure 8, where a rigid wall as new obstacle has been introduced. This example shows, that the hybrid rigid body model has to be checked for contact. Each time when contact appears during the simulation, the formation of rigid bodies and local finite elements changes and so the hybrid rigid body model has to be adapted. Such modifications are also required in the case of failures or fractures of components. The latter concept has later to be transferred to the multi rigid body analyses with an MBS analysis system.

4.3 Rigid body model

In Figure 9, the results of the finite element and the rigid body model are compared. Up to the first contact with the ground, the correlation is excellent. Due to different contact models for the finite element and the rigid body simulation, the collapse starts to differ. Another point to be mentioned is that the connections of the rigid bodies are only cylindrical joints so far. The use of translational joints and a more detailed multi body system may

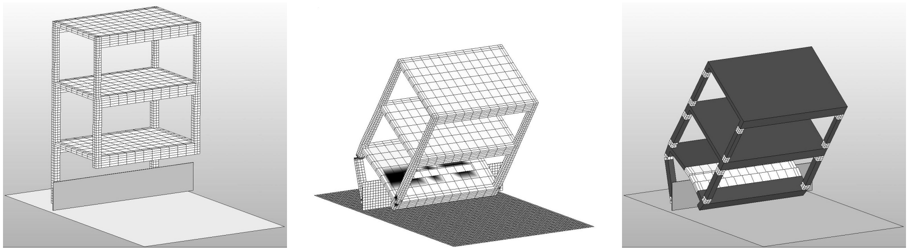


Figure 8: FE-simulation, strain rate analysis and hybrid rigid-body model with rigid wall as obstacle

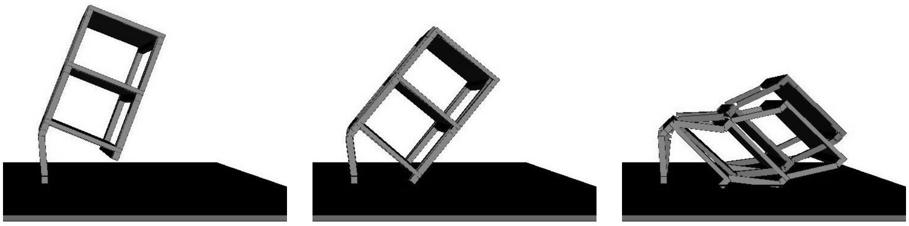


Figure 9: Comparison of finite element and rigid body model at different time states

reduce the differences.

However, at this point of work in the research program it is attempted to gain experience and find rules to create appropriate rigid body models for a realistic simulation of collapses.

5 Conclusions and Outlook

Within this contribution, the general possibilities of modeling building collapse by means of multi body systems taking advantage of the experience from fully FE simulations is discussed. It has been shown, that rather simple multi body systems, which require far less computational effort than corresponding finite element models lead to very similar results, if the multibody system contains the proper subsystems with hinges and nonlinear spring elements at the correct locations. This approach allows to develop a simulation process for multi body systems, hedged by finite element solutions, taking finally also uncertainties by fuzzy analysis into account. Especially for fuzzy algorithms, very efficient simulations are needed because extremely repetitive deterministic simulations have to be carried out. Important for the discretization of the MBS is the proper detection of evolving contact during the collapse. Each time a contact event happens, subsystems with hinges have to be included at specific locations of the MBS. This also holds in the case of fracture events. With the experience gained through the global FE simulation and the nonlinear characteristic resistance curves from the detailed FE models, it is possible to create a database of subsystems, from which optimal MBS for the simulation of the collapse process can be generated, almost automatically, or with little effort by the analyst who uses the developed program.

6 Acknowledgment

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