ON FUNDAMENTAL CONCEPT OF STRUCTURAL COLLAPSE SIMULATION TAKING INTO ACCOUNT UNCERTAINTY PHENOMENA

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Abstract. The simulation of controlled structural collapse using explosives faces the problem of the quantification of structural parameters. The latter has to be accomplished on the basis of only few data, which may additionally be characterized by vagueness, e.g. due to uncertain measurements or changing reproduction conditions. This uncertainty has to be taken into account within a consistent analysis. As the simulation of collapses of real world structures with conventional finite element models requires extreme computational effort, this paper addresses an efficient approach for the simulation of structural collapse based on consistently simplified multibody models, that simultaneously allow for the investigation of uncertainty.

Keywords: Demolition, explosives, multi-level simulation, multibody dynamics, uncertainty, fuzzy analysis

1. Introduction

A controlled structural collapse is often requested for dilapidated buildings. To provide a safe as well as an economically reasonable demolition of such structures at the end of their lifespan, a careful planning of the tearing-down process is required. A prime advantage over alternative demolition techniques (e.g. using wrecking balls or special demolition devices) is that the cost intensive application of man power and equipment is primarily

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limited to drilling holes for the explosive charges in pre-determined zones of the building or structure. The basic idea of a blasting strategy is simply to eliminate vertical supports of the structure by controlled blasting exploiting the forces of gravity in an optimal fashion.

For a long time, the determination of an appropriate blasting strategy has been based upon the acquired experience and knowledge of demolition experts. According to this knowledge, decisions about the number, the placement of the explosive charges applied and the course of the ignition time-points were made. Various accidents and failures at real world blasting events in the past, however, demonstrated that empirical approaches are prone to errors. This is a result of the fact that it is extremely difficult to make prognoses on the accurate dynamic behavior of the induced collapse process. This also holds for the precise position of the explosive charges with respect to the desired collapse result, and also for the ignition time-points as well as ignition sequences of the charges.

To this respect, computer simulations are helpful which form a powerful tool to improve the control of the collapse of buildings, and to figure out optimal blasting strategies.

A lot of research has been carried out on the prevention of hazardous structural collapses. However, only some computer-based investigations on volitional demolitions of moderate complex structures by means of controlled explosives, such as Hartmann et al. (1994), Isobe and Toi (1998) or Kabele et al., (2003) can be found in the literature. In this context, investigations on the dynamic response of structures due to extreme loads like explosion, impact or earthquake have to be mentioned (Meguro and Hakuno, 1992; Meguro and Tagel-Din, 2002; Kaliszky and Logo, 2006). Much of this work is associated with the so-called progressive collapse (e.g. Kaewkulchai and Williamson, 2004; Astaneh-Asl, 2003; Starossek, 2006). One reason for the emergence of the research at this area was the collapse of the Ronan Point Apartment in 1968. Ronan Point was a 23-storey tower block in Newham, East London, which suffered a fatal structural collapse due to a natural gas explosion on 16 May 1968, that caused the progressive collapse of the whole South-East corner of the building. The 9–11-collapse of the world trade center has led to a drastic increase of research in the area of progressive collapse in recent years.

Nonetheless up till now, there is still a lack of generally applicable and holistic simulations for controlled blasting of complex large scale structures. Within this respect the complete basis of modelling has to be considered: The structural model and structural parameters have to be established on the basis of plans, drawings, measurements, observations, experiences, expert knowledge, codes and standards. Structural parameters have to be specified that represent geometry, material and detonation time of the applied explosives (fuses). Very often, certain information regarding structural models and precise values of structural parameters do not exist.

Thus for realistic structural analysis and safety assessment uncertainty must be appropriately taken into consideration. Different methods are available for mathematically describing and quantifying uncertainty. Characteristic concepts are probability theory (Madsen et al., 1986), including subjective probability approach (Wright, 1994) and Bayes-methods (Stange, 1977), interval mathematics (Alefeld and Herzberger, 1983), convex modelling (Ben-Haim and Elishakoff, 1990), theory of rough sets (Pawlak, 1991), fuzzy set theory (Bandemer and Gottwald, 1995), theory of fuzzy random variables (Krätschmer, 2001) and chaos theory (Kapitaniak, 2000). The selection of one of this models is governed by the existing databases. In our contribution is presumed that the databases require the application of the fuzzy set theory, i.e., the uncertainty model fuzziness.

Summarizing, the focus of the presented project is on the simulation of the controlled collapse of complex large scale structures and the design of blasting strategies based on efficient simulation models using multibody dynamics under particular consideration of uncertainty.

2. Deterministic simulation of progressive collapse

A realistic but also efficient simulation of the collapse of complex large-scale real world structures induced by controlled explosives demands a sophisticated simulation model. This simulation model has to cover the dynamics of the entire collapse process, triggered through the ignition of the explosive charges along with the dead load of the structure. At the end of the collapse process, the debris hill as the final result should be obtained. To map all possible phenomena during the blasting process, the simulation model applied has to be based on a multi-level model.

To this end, a three-level approach is useful to capture most effects: On the first level (local level or micro-level), the effects of the exploding charges are modelled such that the volitional damages can be captured and described. On the second level (near field level or meso-level), the effects of the local damages on adjacent structure components are analyzed. These two levels provide a knowledge basis which allows to model the dynamics of the collapse of the entire structure on the third level in an efficient fashion (global level, far field level or macro-level) including relevant fracture processes and relevant contact mechanisms.

For the uncertainty analysis, which requires a large number of deterministic simulations of the collapse, a very efficient computer model is necessary. Therefore the physical core of the simulation model on the global level is based on a so-called “special multibody system (special MBS)” that is tailored to the realistic and efficient simulation of structural collapse, particularly to the major collapse kinematics.

2.1. USING MULTIBODY MODELS WITHIN THE SIMULATION OF STRUCTURAL COLLAPSE

The application of rigid multibody models takes advantage of the typical collapse behavior. In such a collapse the deformations of distinct areas of the structure – considering specified periods of time – are small compared to zones of accumulated damage and failure within the structure. Hereby, the zones of accumulated damage are modelled by means of multibody subsystems that are specifically developed for individual load cases and failure mechanisms supported by additional finite element analysis on the global and near field level. Then rigid and non-rigid zones can be defined for certain time segments of the collapse. Figure 1 shows the relation between the individual simulation models.

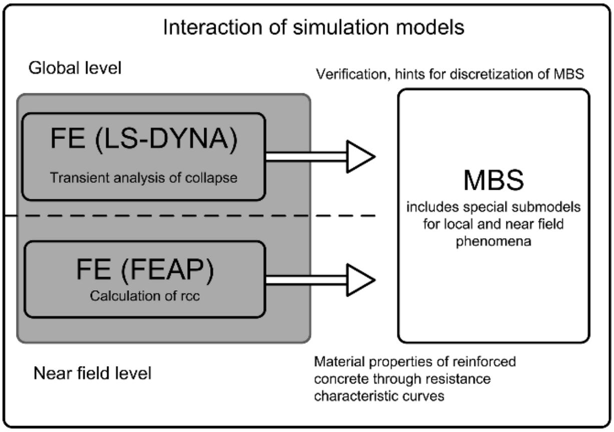


Figure 1. Relation between finite element and multibody models

The multibody subsystems are specifically designed using rigid bodies, constraints and, in particular, appropriate force elements to achieve a realistic approximation of the behavior of reinforced concrete during the collapse process. The force elements use pre-calculated so called resistance characteristic curves (rcc) that are determined by a priori finite element analysis (FEAP) on a near field length scale level using e.g. an elasto-plastic damage model for reinforced concrete.

Also transient finite element calculations (LS-DYNA) are carried out on the global level to gain experience about the proper discretization of the multibody model. This includes the development and selection of appropriate multibody subsystems as well as the distribution of the subsystems within the entire multibody model. To this respect, the development of the multibody model is linked with global transient finite element methods providing a solid basis for verification of multibody subsystems, see Fig. 2.

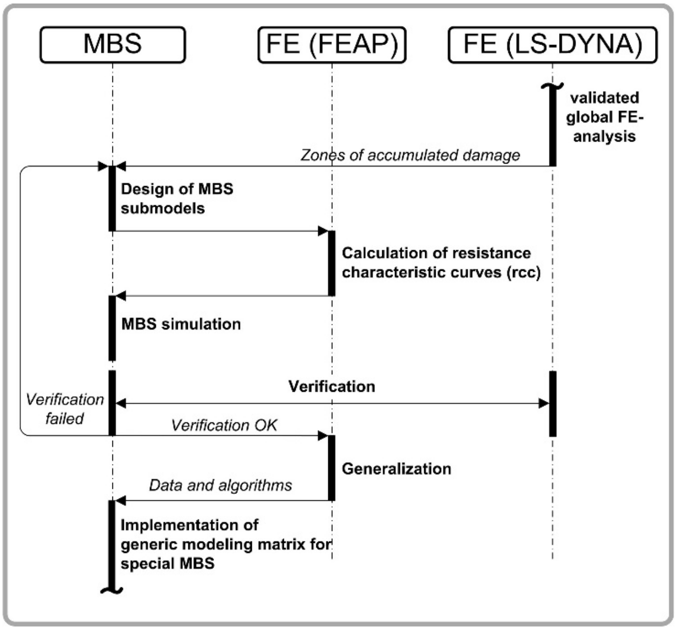


Figure 2. Communication between applied simulation models

Based on validated global finite element analysis of representative real world collapse processes using explicit LS-DYNA (Hallquist, 1998, 2005), typical zones of accumulated damage are identified. The corresponding failure mechanisms are modelled by tailor-made multibody subsystems, that are designed using rigid bodies, constraints and force elements. The nonlinear character of those force elements is calculated by finite element analysis, applying FEAP (Taylor, 2001).

2.1.1. *Reinforced concrete models for zones of accumulated damage and determination of rcc*

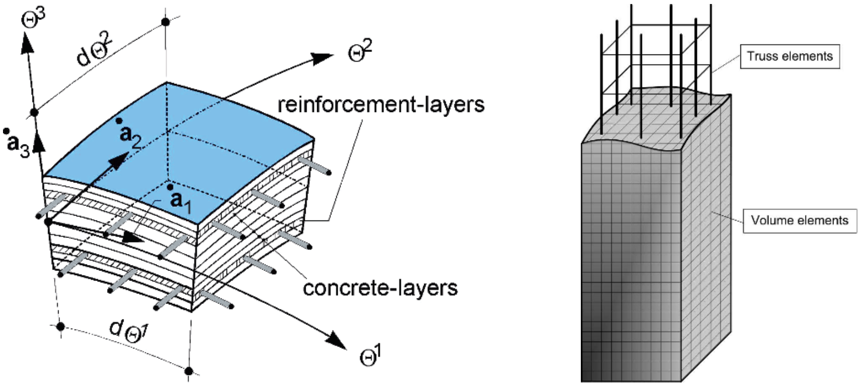
To achieve a realistic approximation of the behavior of reinforced concrete during the collapse process, pre-calculated resistance characteristic curves (rcc) are used. Those rcc are determined by finite element analysis using an elasto-plastic damage model for reinforced concrete used in standard structural members of the complete structure. The analysis and the used material model are described in the following.

Material model
The material model applied depends on Krätzig and Pölling (2004) and is a close-to-practice elastic-plastic damage theory model for reinforced concrete. The advantage is the minimum number of material parameters and their determination by standard experiments. It is implemented in the framework of the finite element program FEAP (Taylor, 2001).
To model the behavior of concrete in compression and tension realistically, a combination of plasticity as well as continuum damage theory is used. Both are formulated stress-based which is more fitting for the analysis of the investigated reinforced concrete structures (Pölling, 2000). To avoid localization effects a smeared crack concept and the use of fracture respectively crushing energy is chosen. For details we refer to Hartmann et al. (2008).

Reinforcement is typically used as bars in reinforced concrete structures, so only uniaxial steel behavior is needed. At least elasto-plastic behavior is required for a failure analysis. More applicable models could be found in Hofstetter and Mang (1995) and Chen (1982).

Discretization with finite elements
Reinforced concrete is represented by superposition of the material models of the constituent parts of its components concrete and steel. Depending on the type of problem, the structural part is represented as a volume element or a continuum-based multi layer shell element (Krätzig and Jun, 2002). The reinforcement is either represented by a thin layer within the shell element (Fig. 3a) or a discrete truss element representing each single bar (Fig. 3b). As a consequence perfect bond is assumed. The integration of the constitutive equation is based on the return map algorithm described in Simo and Hughes (1998). Changes and further implementations regarding the specific requirements of the material models for reinforced concrete can be found in (Pfister et al., 2006).

Determination of resistance characteristic curves
The determination of the resistance characteristic curves is conducted based on a FE-Program using the above described material models and elements. It is to be emphasized that the shell element is limited to plates and simple beams due to the complex construction of reinforcement in intersections and columns (stirrups). The stress resultant, which are needed as resistance for the subsystems in the special multibody simulation, can be determined by means of an integration of the stresses. Regularly, the approximation of structural members is made by one shell element representing the height or thickness, so that the stress resultants can be calculated between two



(a) Continuum based multi layer shell element

(b) Volume and Truss elements

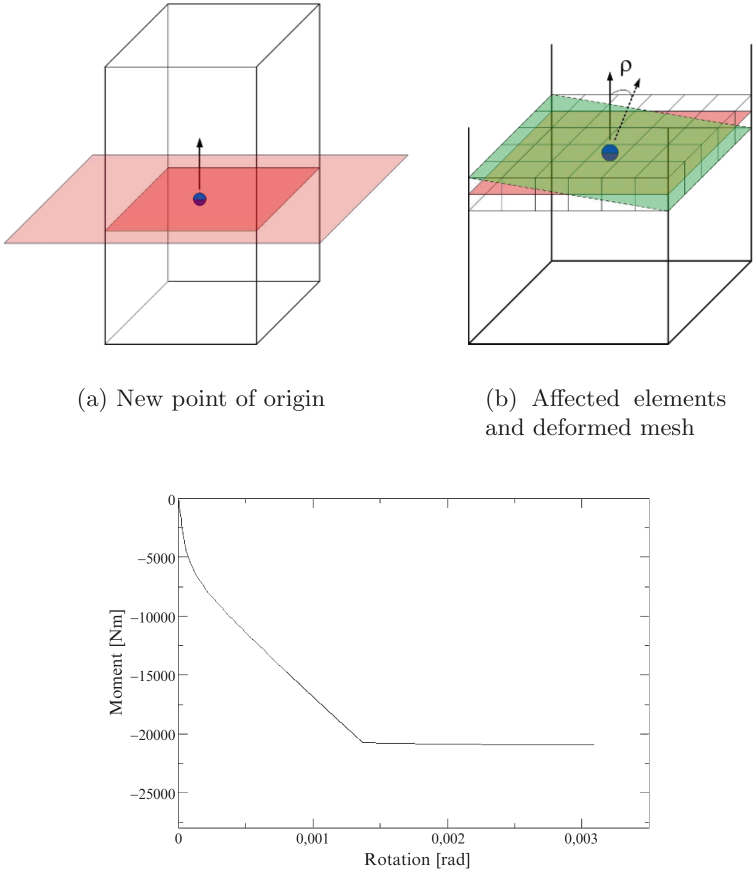
Figure 3. Used types of elements

elements. Using volume elements the calculation of the stress resultants requires a given cross section, such that additional data is needed. For one or more locations in the mesh a new arbitrary point of origin is chosen. Along with a defined normal direction, a surface $E: \ \boldsymbol{p} \cdot \boldsymbol{n} = 0$ is created within the mesh (Fig. 4a). By an intelligent search of the 'corresponding' integration points to this surface, the stress resultants, e.g. $M_y = \int_A \sigma_x \cdot z \cdot dA$, can be calculated. The displacements of the affected nodes lead to the corresponding translational and rotational deformations of the considered zone (Fig. 4b). For different load scenarios the required rcc for the subsystems in the special multibody systems are obtained (Fig. 4c).

2.2. VERIFICATION WITH FINITE ELEMENT ANALYSIS

A verification of the multibody analysis is accomplished with global finite element models of the investigated structures, which are validated against the real collapse process in the form of a visual comparison with video sequences.

To obtain an accurate prediction with finite elements, and consequently to achieve the desired validation of the finite element model, a numerical analysis tool has to provide several capabilities. First of all, the numerical tool must represent the dominant mechanical phenomena which appear during the collapse, e.g. initial wave propagation after detonation, deformations and motions of building parts, emerging local zones of accumulated damage, development of initial kinematics and contacts between building



(a) New point of origin

(b) Affected elements and deformed mesh

(c) Calculated rcc

Figure 4. Procedure of rcc calculation

fragments. In this contribution, the finite element method is used applying an explicit time integration algorithm (the central difference scheme) as numerical analysis tool. In combination with the central difference method, the finite element method is an efficient and accurate tool, offering great flexibility for analyzing arbitrary geometries and materials. Corresponding analyses are described in detail in Section 5.2.

The modelling and validation process is carried out as follows. First, the geometry is mapped onto a CAD system. The CAD model is then used to discretize the structural system in terms of finite elements. The specific requirements needed for the element and material formulation are described in Section 5.2. Subsequently, the analyses are performed and compared visually with a sequence of video snapshots in order to evaluate the motion of the collapsing building.

The results of this validation are used to verify the kinematics, obtained by the simulations of the multibody systems. Furthermore, in these models, local zones of accumulated damage which act like hinges can be identified. Parts which are connected to two or more such local zones can be regarded as fragments showing a rigid body like behavior. In this way, the discretization of the multibody system is supported and safeguarded.

3. Investigation of uncertainty

Structural collapse is strongly influenced by data uncertainty. The choice of an appropriate uncertainty model depends on the characteristic of the uncertainty present in the problem description and the boundary conditions. Mostly well developed probabilistic models are applied to take account of uncertainty. In structural collapse simulation however, engineers have to quantify structural parameters on the basis of only few data, which may additionally be characterized by vagueness, e.g. due to uncertain measurements or changing reproduction conditions. Moreover, some expert knowledge and linguistic assessments are required to be incorporated into the modelling. Hence, engineers only have an idea concerning the range of the values of these parameters and some estimate which values are more possible to occur than other ones. For modelling such information adequately a non-probabilistic uncertainty model that considers sets of parameter values together with subjective weighting information inside the set is needed in this context. Fuzzy set theory and fuzzy probabilistic theory provide the most powerful basis for a realistic and reliable modelling. The former permits the modelling of uncertain parameters, and a subjective assessment of degrees describing on the particular elements belong to the set by means of membership functions. This uncertainty model offers the chance for appropriately taking account non-stochastic uncertainty, which frequently appears in engineering problems without making any artificial assumptions concerning the validity which cannot be proven definitely. The fuzzy probabilistic uncertainty model represents a generalized uncertainty model and joins elements of fuzziness and probability (Möller and Beer, 2004).

Thus in this project it is presumed that the quantification of uncertainty has to be performed exclusively on the basis of vague information and expert knowledge, as it frequently appears in the case of structural collapse analysis of real world examples. This non-probabilistic uncertainty demands the application of the appropriate uncertainty model fuzziness for uncertainty quantification and the application of the assigned analysis methods designated as fuzzy analysis.

4. Software aspects

In order to model real-world systems for computer-aided destruction, a user-friendly and efficient software system is essential. Efficiency is required because a large number of simulation experiments has to be accomplished. As a consequence, all partial models used for the controlled blasting (e.g. product model, MBS models, MBS subsystems with resistance characteristic curves etc.) need to be modelled efficiently and should be modifiable without major effort. For the development, verification and employment of an efficient and close-to-reality blasting simulation environment, in particular a user interaction along with appropriate visualization capabilities of both the model parameters and the simulation results is crucial.

Experiences in optimization of blasting strategies have shown that the implementation and integration of various acquainted as well as new tools into a simulation system are necessary. In the following, a Java-based prototype software system is presented that serves as a “Computational Steering Environment” providing interactive control and visualization capabilities during blasting simulations.

In this section, a brief overview of the underlying structure of the prototype software system and the used simulation model is given. In addition, the key components of the software architecture are briefly explained.

Figure 5 is a graphical representation of the simulation concept and the different submodels as constituents of the total simulation model. Submodel (a) represents the product model for the “demolition using controlled explosives” which serves as a database containing all relevant data needed for the global level simulation (e.g. geometry, material data of the parts of the building, the details of the preparatory work like modifications of the static structure before ignition of the explosives, potential events such as locations and ignition times of explosive charges). Based on these data, along with the results of the different submodels of the global level (d) as well as the lower levels (e), the submodel “simulation manager” (b) creates a model description of the special MBS (c1).

The modelling process takes into account special knowledge (f) that is implemented in the simulation manager submodel. Then, the modelling process can be executed by means of the simulation system depending for example on upcoming events during the simulation. Hereby, the process can be partitioned into individual time steps according to the needs of

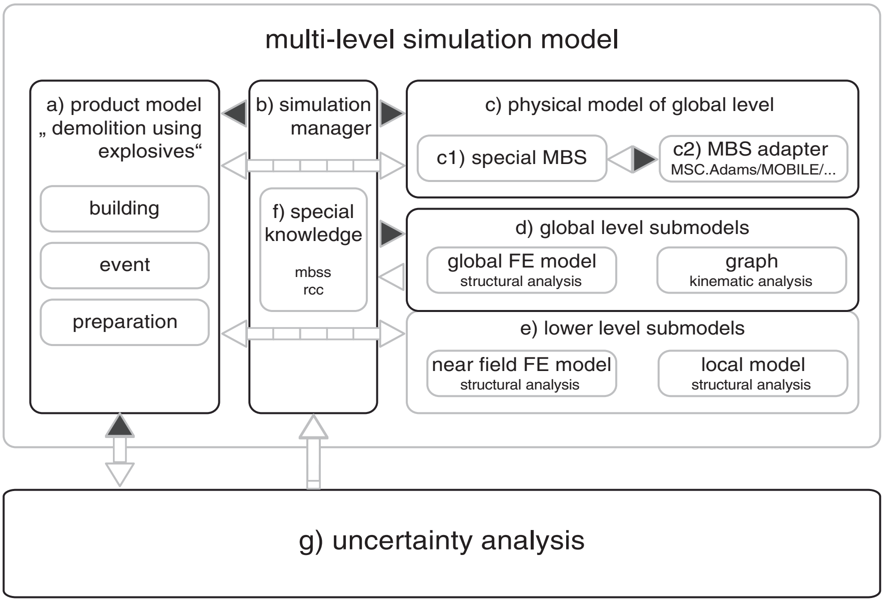


Figure 5. Schematic presentation of the simulation model for the global level of multi-level-problem and coupling to uncertainty analysis

a given problem. The special knowledge for the simulation manager submodel (b), which is providing adequate MBS subsystems, is acquired in collaboration with the involved partner research institutes. In particular, the resistance characteristic curves (rcc) for the nonlinear force elements of the MBS subsystems are computed by the partner Institute of Reinforced and Pre-stressed Concrete Structures in Bochum, based on a near field finite element analysis in zones of accumulated damage. Hereby, specific material models for dynamically loaded reinforced concrete are applied, see Section 2.1.1.

Furthermore, the global MBS models of representative reference systems are verified by transient global finite element (FE) simulations performed by a further partner, the Institute for Mechanics of the University at Karlsruhe, see Section 2.2.

The creation and solution of the system equations of the MBS model is accomplished by a MBS software that is applied by the special MBS submodel via a specific MBS adapter (c2). Currently, the MBS software system MSC.Adams (MSC.ADAMS) is used which fits best. The above mentioned submodels (a) to (c) of the simulation model are implemented as distributed, object-oriented software components that are integrated into the simulation system to allow for a holistic multi-level simulation of the demolition process. This simulation builds the foundation for the uncertainty analysis (g), see Section 3.

A specific simulation manager has been developed which is further described in Hartmann et al. (2008).

5. A first numerical example

5.1. CHOSEN REFERENCE SYSTEM

As a real world example for the blast simulation, an old storehouse in Thüringen has been chosen which has been deconstructed by blast in 1998 (Fig. 6). 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 m, the width is 12 m, leading to an approximate overall mass of about 1,900 t.

In the simulation, the collapse has been carried out in two steps. In a first explosion, two rows of columns in the ground floor has been removed, after 4 s by a second explosion, a third row in the ground floor has been deleted as depicted in Figs. 7 and 9.

The degradation, caused by the first explosion has proved as to be not sufficient to induce the collapse of the building: The structure remained staying for 4 s on the two remaining rows of columns. Only after the destruction of these 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 and started to break into pieces.

Figure 6. Reference structure in Weida/Thüringen

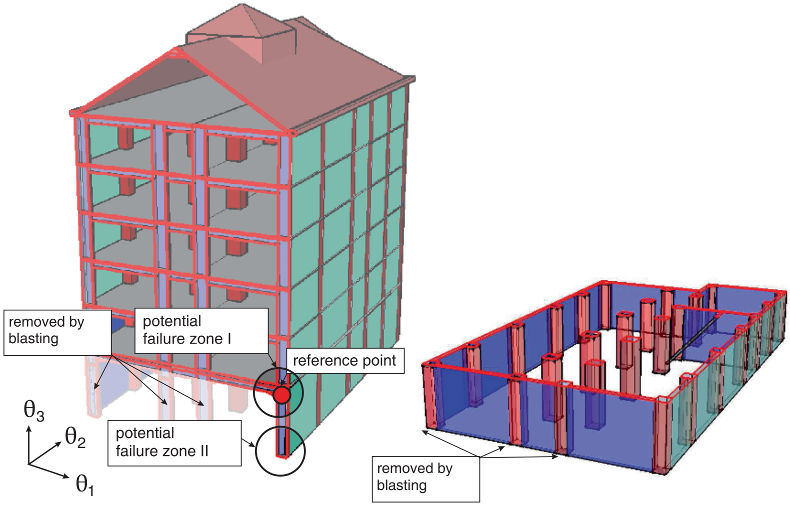


Figure 7. Storehouse – to be demolished with the aid of controlled explosives

5.2. FINITE ELEMENT ANALYSIS

The structural analysis has been based on the commercial FE-program LS-Dyna® which uses a central difference method for time integration (Hallquist, 1998, 2005). For discretization of the structural parts, one-point under-integrated hexahedral elements with hourglass stabilization (Belytschko and Bindemann, 1993) have been chosen, which perform excellently without any locking.

For all concrete parts, a piecewise linear plasticity material model is used. The parameters, describing concrete like behavior were obtained by calibration with rather simple experimental examples. Although, the material model does not allow detailed modifications concerning e.g. reinforcement, the reached approximation for the mass-dominated problems investigated, has rendered reasonable results used to support the generation of the MBS. The potentiality of element failure, which needs to simulate the appearance of local zones of accumulated damage (hinges) during the collapse event, has also been implemented in the material model. Then, every time an element reaches a specific plastic strain, it is removed from the computation. With this procedure the development of rigid body models as mentioned in Section 5.3 is supported and validated. With respect to accuracy, it is acceptable to use the same material model for each simulation. This has to do with limited amount of knowledge and information provided by technical documentation available on the concrete and steel used. Existing lacks of information are, therefore, compensated through application of uncertainty algorithms.

Another approach focusing on a more detailed modelling of the failure of brittle materials is the usage of discrete models described for 2D problems in a rather small scale in Ibrahimbegovic and Delaplace (2003) and Delaplace and Ibrahimbegovic (2006). For the modelling and especially the discretization of multi-storey buildings in practical applications it is a long term goal to include discrete element models, however, the computer resources required are tremendous and beyond the range of the current project described in this paper.

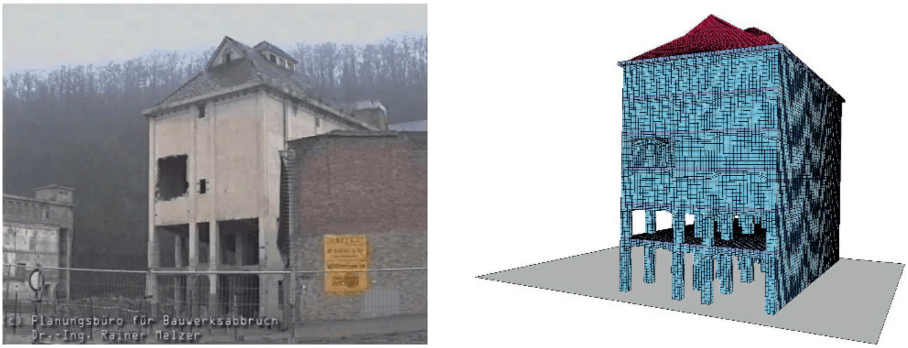
Each time when contacts happen during the collapse, the kinematical configuration of the simulated structure changes abruptly. Hence, also the correct determination of contacts within parts of the building as well as between them and the ground is important to obtain a realistic collapse behavior of the model used. For this reason, fast automatic contact search algorithms are implemented in LS-DYNA®. Albeit these algorithms show very good performance concerning accuracy and computation time, the search for contact consumes a considerable amount of CPU-time within the whole simulation because each surface segment of the FE-mesh has to be considered. The chosen contact formulation is a penalty-based node-to-segment algorithm to capture the baseplate contact, and a segment-to-segment algorithm between building fragments. The baseplate has been modelled using four-node shell elements, assumed as to be rigid, representing the contact segments for the base plate. The discretized structure depicted in Fig. 8b, consists of $82,867$ hexahedral finite elements.

The results of a simulation based on the planned blasting strategy (Fig. 9) can be seen in Fig. 10. Unfortunately, the existing documentation of the real collapse in 1998 is confined to only one video, which makes comprehensive validation of simulations difficult. Nevertheless, the take-off phase of the collapse is fairly realistically mapped with respect to the data quality available.

5.3. MULTIBODY ANALYSIS

The multibody analysis-based simulation of the collapse of the above storehouse is entered after blasting away the first three rows of columns within the ground floor of the structure. In Fig. 11, the created multibody system established is shown schematically.

The zones of accumulated damage are modelled by means of specific multibody subsystems. In particular, the failure of the columns within the ground floor govern the rotation of the structure. Failure areas of columns are modelled by using revolute joints in association with rotational nonlinear force elements. The nonlinear characteristic of the forces has been calculated by a finite element analysis, as described in Section 2.1.1. For



(a) (b)

Figure 8. Reference structure in Weida/Thüringen – photography (**a**) and finite element discretization (**b**)

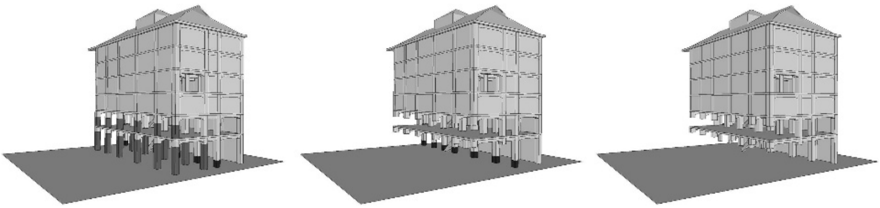
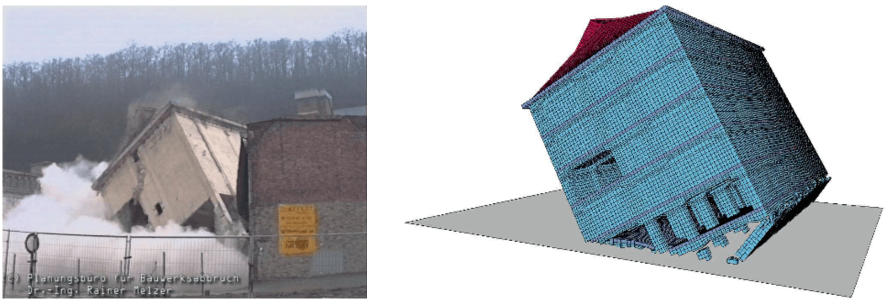


Figure 9. Blasting strategy in order to achieve the collapse kinematics



(a) (b)

Figure 10. Reference structure in Weida/Thüringen – video sequence (**a**) compared to simulation results (**b**)

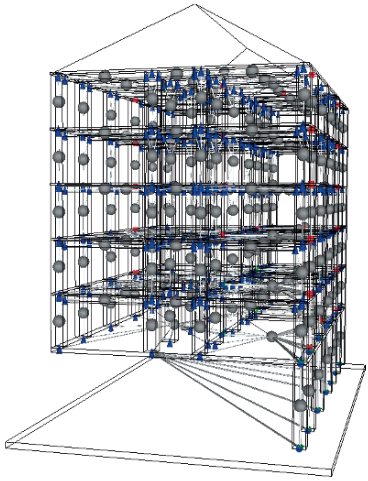


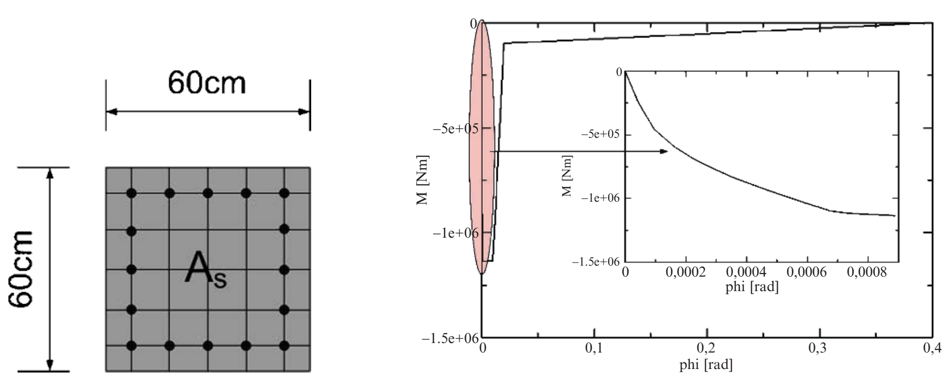
Figure 11. MBS model of reference system

example, for the ground column the dimensions could be taken over from design drawings, whereas the amount and position of reinforcement have been unknown. The same holds for the material data for concrete and reinforcement. To cover these uncertainties fuzzy rcc are determined as described in Section 5.4.

The finite element mesh chosen represents the characteristics of a reinforced concrete column (see Fig. 12a). For the rotational force element a bending moment is required representing the resistance of the column subjected to the rotation of the revolute joint. To take into account the interaction of bending moment and normal force, the weight of the building concerning one column has to be transferred into a normal force. To calculate the stress resultants and deformations, loads corresponding to a normal force and bending moment are applied on nodes of the finite element mesh. By increasing the loads up to the failure of the structure, one obtains the rcc. One deterministic solution of a calculated rcc is shown in Fig. 12b.

Figure 11 shows the simulation of the progressive collapse: After a certain amount of rotation, the structure touches the ground leading to further failures, in particular, within the ceiling.

The model applied contains in total 255 rigid bodies, 19 revolute joints, 43 rigid joints and 639 force elements. Contact of all rigid bodies with the ground is considered. In this case, the computation has been carried out by using the MSC.ADAMS (MSC.ADAMS) program system, applying the penalty regularization-based "Poisson" model with an appropriate coefficient of restitution, see Fig. 13.



(a) Cross section of rc–column

(b) Calculated rcc

Figure 12. Calculated rcc for the ground column

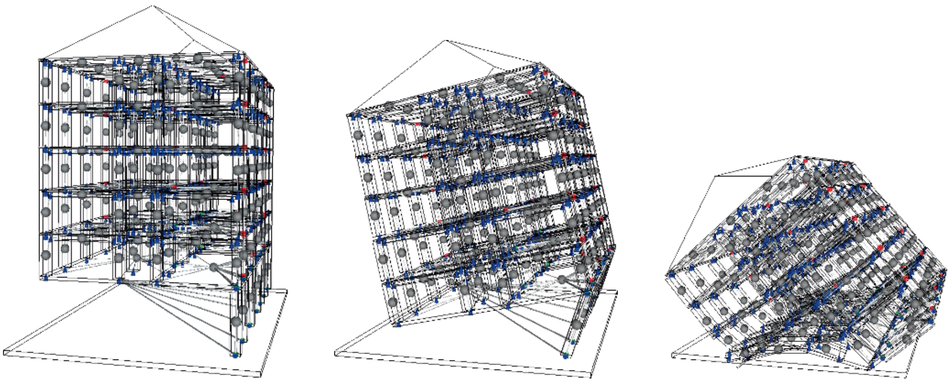


Figure 13. MBS simulation of reference system

The multibody simulation shows an ample coincidence with the finite element analysis for the same process as demonstrated in Fig. 14. It should be pointed out that the comparison of computational costs underline the MBS approach: In contrast to the finite element simulation that requires 31 h for 1.7 s duration in reality, the MBS simulation took only 15 min using a comparable one processor hardware configuration in both cases.

In principle, alternative approaches combining flexible and rigid parts in a single model (see e.g. Ibrahimbegovic et al. [2003] are possible and used in the own global FE verification using LS-DYNA (see Mattern et al. [2006]). Within the concept of this study, however, focus is placed on rigid body systems solely.

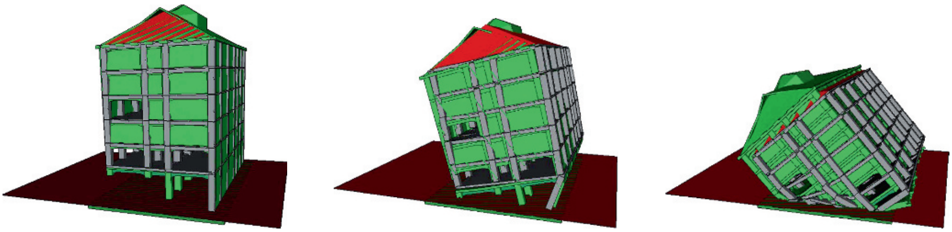


Figure 14. Comparison of finite element analysis (green) and MBS simulation (grey-red)

5.4. FUZZY ANALYSIS

The technical documentation of the structure Fig. 7 as well as the information about the used material and the amount of concrete reinforcement are often incomplete. Therefore a fuzzy structural collapse analysis is required.

This analysis is performed in two steps:

1. Determination of the non-linear fuzzy resistance characteristic curves $\tilde{k}$ of the selected potential failure zones (Fig. 7)
2. Fuzzy multibody analysis of the structural collapse based on the special multibody system, where determined fuzzy rcc $\tilde{k}$ are fuzzy input values

The uncertain results enable engineers to assess the selected blasting strategy forming the basis for improved design and dimensioning.

Determination of fuzzy resistance characteristic curves (fuzzy rcc)
Exemplarily the fuzzy rcc of the potential failure zone I (Fig. 7) is determined. The associated fuzzy function expresses the dependency between the rotation φ_2 and the bending moment M_2. The deterministic fundamental solution as given in (Section 2). Examination of the available data has shown that the following structural parameters possess the uncertainty characteristic fuzziness:

- Modulus of elasticity $\tilde{E}_c$
- Tensile and compressive strength $\tilde{f}_c$, $\tilde{f}_{ct}$
- Yield stress $\tilde{f}_y$ of the reinforcement steel
- Amount of reinforcement in the cross section $\tilde{a_s}$

All fuzzy structural parameters identified are input values of the fuzzy finite element analysis and given in Table 1. Full interaction is assumed between concrete tensile and compression strength according the following equation

$$\tilde{f}_{ct} = 1.40 \cdot \left(\frac{\tilde{f}_c - 8}{10} \right)^{\frac{2}{3}} \quad . \tag{1}$$

TABLE 1. Fuzzy structural parameters

	$\alpha_l = 0$	$\alpha = 1$	$\alpha_r = 0$
$\tilde{E}_c$	$15 \cdot 10^3\,\mathrm{N/mm^2}$	$30 \cdot 10^3\,\mathrm{N/mm^2}$	$52 \cdot 10^3\,\mathrm{N/mm^2}$
$\tilde{f}_c$	$10\,\mathrm{N/mm^2}$	$25\,\mathrm{N/mm^2}$	$45\,\mathrm{N/mm^2}$
$\tilde{f}_{ct}$	$0.479\,\mathrm{N/mm^2}$	$1.994\,\mathrm{N/mm^2}$	$3.349\,\mathrm{N/mm^2}$
f_y	$220\,\mathrm{N/mm^2}$	$420\,\mathrm{N/mm^2}$	$500\,\mathrm{N/mm^2}$
$\tilde{a}_s$	$33.6 \cdot 10^{-4}\,\mathrm{m^2}$	$64.00 \cdot 10^{-4}\,\mathrm{m^2}$	$88.00 \cdot 10^{-4}\,\mathrm{m^2}$

The mapping of the fuzzy input values onto fuzzy result values is performed with the fuzzy finite element analysis as mapping model M.

$$\tilde{E}_c,\ \tilde{f}_c,\ \tilde{f}_{ct},\ \tilde{f}_y,\ \tilde{a}_s \rightarrow \tilde{k}_{M_2,\varphi_2}. \tag{2}$$

In Fig. 15 a partial result of the fuzzy rcc $\tilde{k}_{M_2,\varphi_2}$ for positive rotations $\varphi > 0$ is shown.

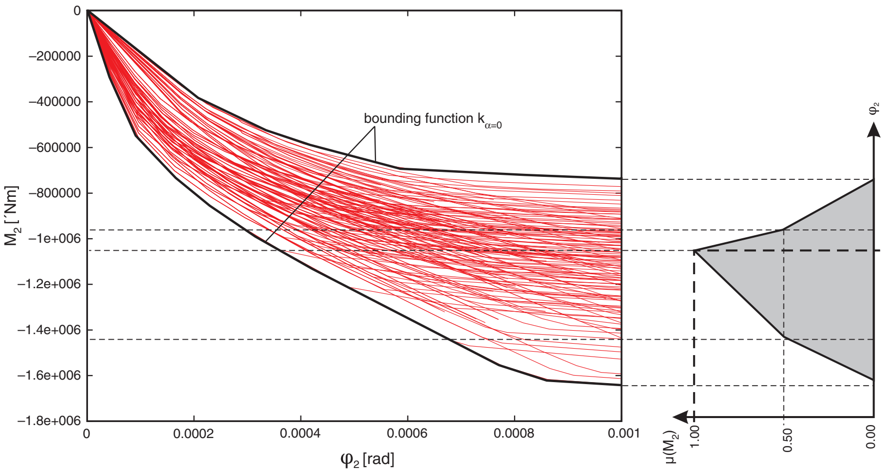


Figure 15. Fuzzy resistance characteristic curves $\tilde{k}_{M_2,\varphi_2}$

Uncertain structural collapse simulation – fuzzy multibody dynamics

The uncertain structural collapse simulation comprises as mapping model the special multibody system (Section 2.1) and the fuzzy rcc of the two potential failure zones I and II (Fig. 7). Depending from the uncertain input parameters different collapse scenarios arise (Fig. 16). The selected blasting strategy, i.e., blasting of the front columns, aims at a tilt collapse.

In the simulation is assumed that hinges develop in the potential failure zone I and II. The resulting kinematics has shown levels for the tilt of the structure. The planned tilt collapse occurs if the displacement $\tilde{d}_{\theta_1}$ (Fig. 16) is zero or negative otherwise a aborted collapse arise. Hereby, the fuzzy displacement function $\underline{\tilde{\theta}}(\tau)$ is used as indicator. This function is obtained as a result of the fuzzy multibody dynamic. The fuzzy functional value $\tilde{\theta}_1(\tau_2)$ at the time $\tau_2 = 1.7$ s represents $\tilde{d}_{\theta_1}$ according to Fig. 16. This result shows that negative displacements may be occur. The question arises which values of the fuzzy input parameters (Table 1) lead to negative $\tilde{d}_{\theta_1}$. An answer can be given by the fuzzy cluster design. According to Eq. (2) five fuzzy input parameters are considered which form a five-dimensional design space $\underline{D}$. The design space $\underline{D}$ may be divided into two subspaces. Points of the permissible subspace $\underline{D}^{[1]}$ lead to a tilt collapse whereas points of the non-permissible subspace $\underline{D}^{[2]}$ cause a vertical collapse. With the aid of the developed algorithm of cluster design (Beer and Liebscher, 2008) the permissible subspace $\underline{D}^{[1]}$ may be determined. For any further details we refer to Hartmann et al. (2008), Möller et al. (2008), Liebscher, (2007).

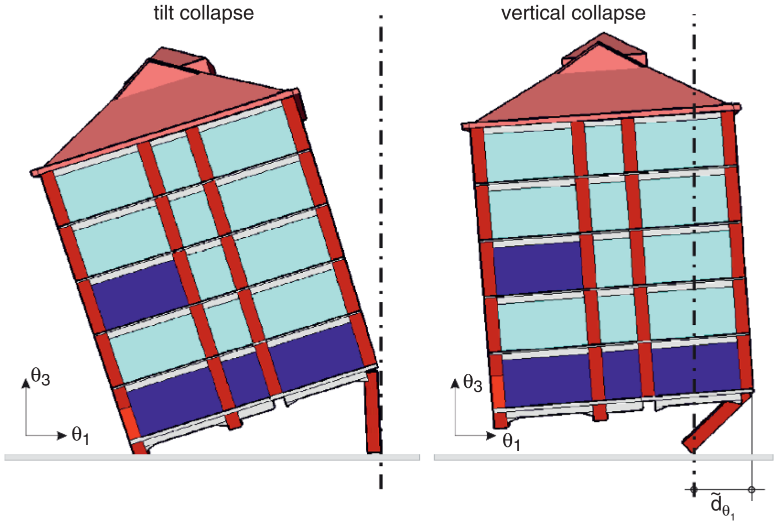


Figure 16. Possible collapse scenarios due to data uncertainty

6. Summary and conclusions

This paper demonstrates that the simulation of the demolition of buildings by means of controlled explosives carried out on the basis of multibody models is efficient and close to reality.

The verification of the multibody models using validated transient finite element calculations evidences the correctness of the approach. Compared to finite element calculations, simplified multibody models are far less time consuming. Considerable reductions of calculation costs are crucial preconditions for a good performance of the uncertainty analysis. In addition MBS models allow practical engineers to judge their blasting strategy more safely and with limited effort.

The presented concept and first results of an ongoing research project show in particular, that the consideration of uncertainty substantially improves the process of designing demolition strategies as well as the safety of a blasting project. Using uncertainty analysis, it is possible to find solutions that could hardly be identified with an solely deterministic analysis because of the complex and non-intuitive behavior of collapsing buildings due to a vague information basis.

Currently, the presented concept is extended to large scale structures in densely populated areas where the demands are even higher.

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