

Simulation of an Aircraft Impact on Reinforced Concrete Structures

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1 Introduction

The attacks of September 11, 2001 on the World Trade Center, among several other things, initiated a discussion regarding the safety of nuclear power plants against aircraft impacts. Dealing with this issue, an examination of reinforced concrete structures often has to be included. In the past 15 years, there have been many studies on the resistance to mechanical effects of an aircraft crash. In addition to experimental investigation and analytical consideration, numerical simulations for the assessment of mechanical effects after an aircraft impact have become increasingly important for safety tests.

This article explains the procedure of a practical project for the investigation of a reinforced concrete reactor building exposed to aircraft impact by using simulations with LS-DYNA, ANSYS and optiSLang.

2 Methodology

In order to be able to calculate the response variables of a supporting structure after an aircraft impact considering all loading capacities of the reactor building, the inclusion of a numerical simulation using finite element analysis is necessary. In this project, a dynamic transient finite element analysis is performed in LS-DYNA.

For the numerical simulation, two submodels are created. One for the reactor building, such as consisting of the foundation plate, outer wall, roof or dome, as well as intermediate ceiling. The other model considers the aircraft itself. The partial models are combined to one parametric model with the aircraft being positioned in a chosen impact situation and activated at certain flight speed. Using the parameterized finite element model, variants of the impact situation are simulated. Thus, relevant damage scenarios can be analyzed under maximum loading conditions and be compared with plant-specific assessment criteria.

3 Modeling of reinforced concrete structures

The reactor building is modeled as a 3D model with differently defined areas. In the impact zone of the aircraft, a finer discretization must be carried out. This is done by mapping the composite of reinforced concrete using a discrete spatial modeling of concrete and reinforcing steel (see Fig. 1).

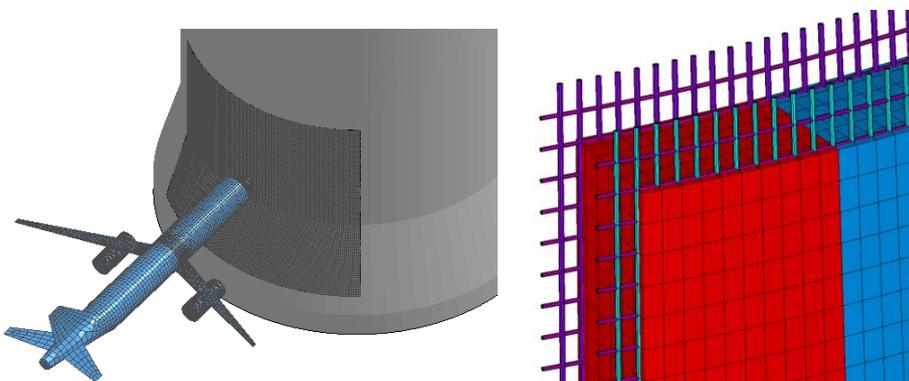


Fig. 1: Detailed modeling of the reinforced concrete in the impact area

The concrete is discretized by means of volume elements and the individual reinforcing bars by means of beam elements. The reinforcement quantities are taken from the reinforcement plans. Outside the impact area, the net density can be increased and the properties of the reinforced concrete can be regarded as a smeared. ANSYS is used in the present case for the modeling.

4 Non-linear material modeling of concrete and reinforcing steel

The material data taken from the quality and fatigue monitoring on the reactor building served as the base for the modeling of the concrete and the reinforcing steel. Thus, the simulation considered a current fatigue-related state of the reactor building.

For impact simulations (especially for penetration tests), the used concrete model must contain the following features:

- consistent description of the concrete strength in the stress space considering the tensile and pressure anisotropy as well as the specific characteristic of shear stress and hardening under triaxial compressive stress conditions
- nonlinear stress-strain behavior [5] (hardening / softening) of the concrete in the pressure and tension zone (modeling of smeared cracking)
- unassociated plastic damage behavior to describe the dilatancy
- strain rate dependency of the concrete compression strength (see Fig. 2)
- robust numerical implementation (especially important for practical project applications!)
- possibility of eroding at certain strain criteria

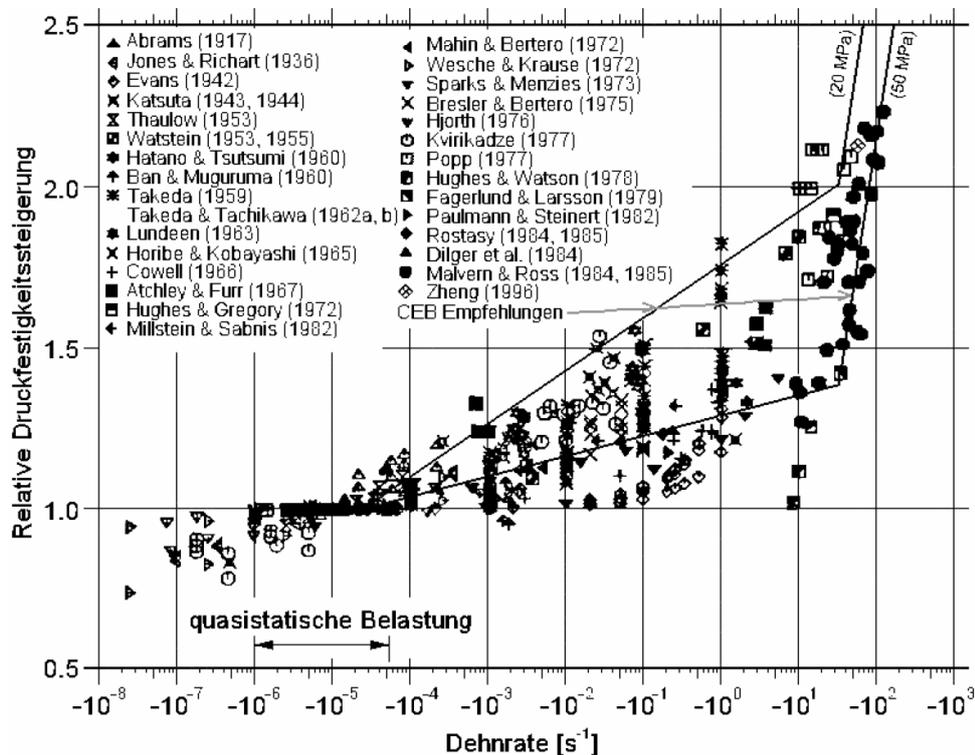


Fig. 2: Dependence of the concrete compressive strength on the strain rate according to [2]

LS DYNA offers a wide range of concrete models, which Dynardo has been using for over 15 years in a variety of non-linear concrete analyses. Depending on the task, large differences in the suitability

and robustness of the individual models can be observed. Therefore, a validation of the material model is very important [7] to be suitable for the task.

In the direct zone of impact, the concrete is modeled using the LS-DYNA material model 16 (*MAT_PSEUDO_TENSOR) [6]. In this material model, different modes of material modeling can be selected. The mode II.C., which is named "tensile failure plus damage scaling", is used. An important aspect for selecting this material model is its numerical robustness as well as its well-comprehensible physical plausibility. However, for the safe use of this material model, some additional settings are necessary to the ones given in the recommendations of the manual [6], [8] (MAT16, section "A Suggestion"). The settings are determined by the verification of concrete tests according to [9], [10] using parameter identification with optiSLang [11]. The recalculation particularly deals with the tabular input, referred to as equation-of-state EOS, as a further failure mode which is dependent on the hydrostatic stress. The verification also considers the dependency of the compression relief module K regarding the volume compression.

The reinforcement is discretely modeled with beam elements and the LS-DYNA material model 24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) [6]. According to [3], concrete steel essentially shows elastical-viscoplastical characteristics under a high stress rate. The material properties in the elastical range are therefore almost unaffected by the strain rate, while a viscous strain-dependent behavior must be considered for the plastical zone. The influence of the strain rate on the mechanical properties of reinforcing steel therefore has a double positive effect on the behavior of reinforced concrete components under high loading rates. Both the increase of strength values, as well as the increase of ductility, leads to a higher performance capacity of the reinforced concrete components. In order to exploit the positive effect in the finite element analyses, strain rate-dependently formulated and idealized stress-strain relations [4] are used.

The finite element model of the reactor building very realistically considers all important failure modes of the reinforced concrete in the impact area as a result of the aircraft impact, such as shear and bending failure or punching. Fig. 3 shows the results from the calculations of test and validation.

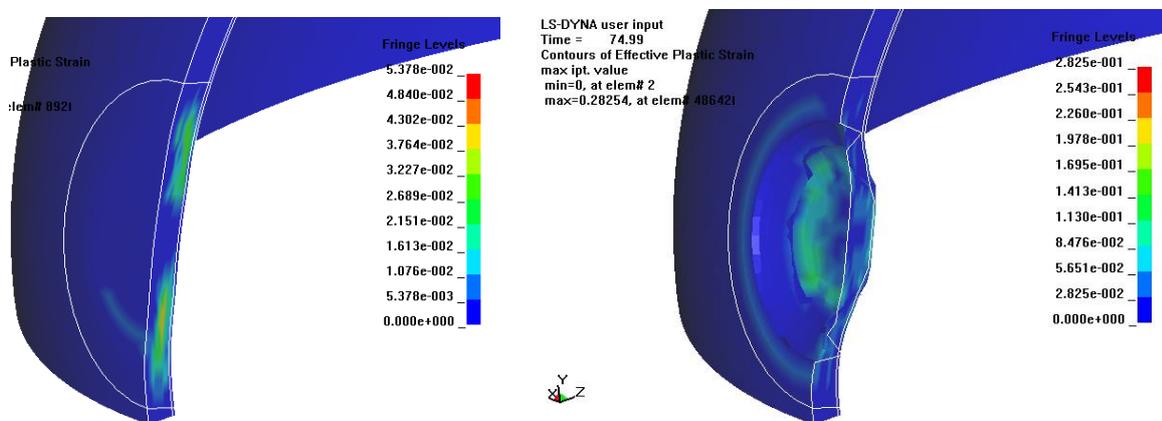


Fig. 3: Validation of calculations of the reinforced concrete: left-combined shear and bending failure; right-punching

5 Resulting load conditions from the aircraft impact

The loads resulting from the aircraft impact can be analyzed quite realistically with the help of aircraft models.

The aircraft geometry is abstracted in LS-DYNA as a shell model. For the finite element discretization, shell elements (Belytschko-Tsay, ELFORM = 2) are used. Fig. 4 shows the model of an A320 in the longitudinal section along the center of the fuselage. In addition, models of the types Airbus A340 and A380 were also created.

The mass distribution, the stiffness (cross-section of the fuselage including the moment of inertia of the wingbox), as well as the plastic limit resistances (failure moments, breakage shear forces, buckling loads) are the most influential factors for the crash behavior and the energy dissipation capacity. The

mass distribution, the stiffness and the plastic limit resistances of the aircraft model are calibrated and verified based on the provided manufacturer specifications.

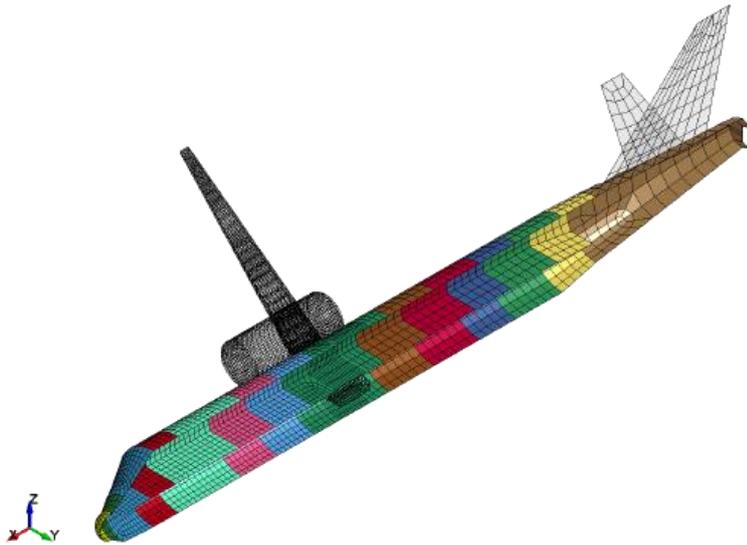


Fig. 4: Section of the A320 aircraft model

6 Validation of calculations and limit evaluation tests using the complete model

The most important assessment criterion for an aircraft model is the plausibility of the behavior of the aircraft structure while crashing into a rigid cylinder (see Fig. 5). It has to be capable of plausibly simulating the assumptions regarding the plastic limit resistances during the impact.

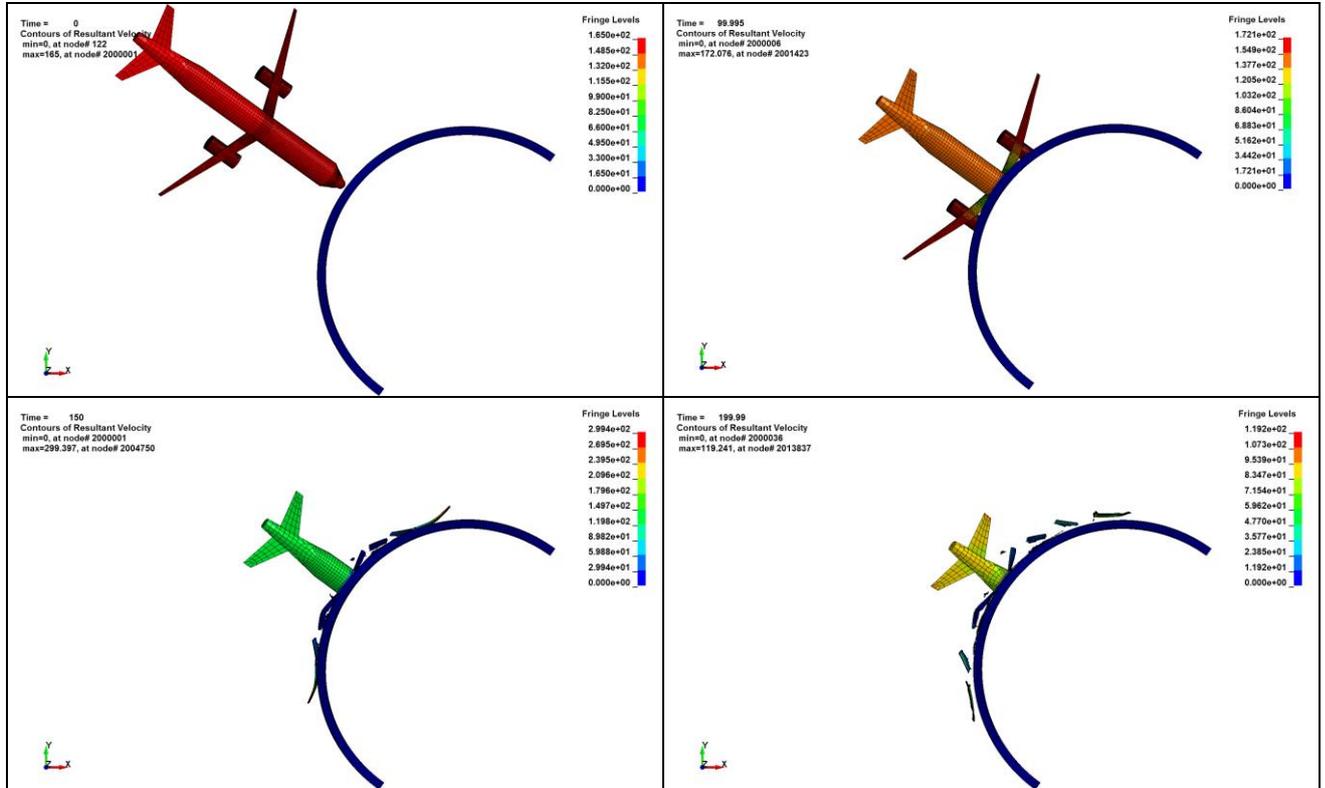


Fig. 3: Validation of impact simulations of an A320 impact on a rigid wall depicted as contour plots of the node velocities for different time points

The moments as well as the normal and transverse forces are evaluated using important cross sections (normal force in typical section of the fuselage, transverse force/moment in the connection to the wingbox, transverse force in the connection to the engine) and are compared with the predefined characteristic values or with the freely accessible data. Furthermore, the simulation model enables the validation of the simulated load-time functions with a simplified approach (e.g. the Riera curve) for the testing of plausibility.

Regarding limit evaluations of airplane impacts, validated complete models are recommended consisting of the reinforced concrete structure (e.g. reactor building) and the airplane model. With the simulation of different impact scenarios, the consistent recording describes the energetic interactions between the aircraft and the reinforced concrete building (see Fig. 6).

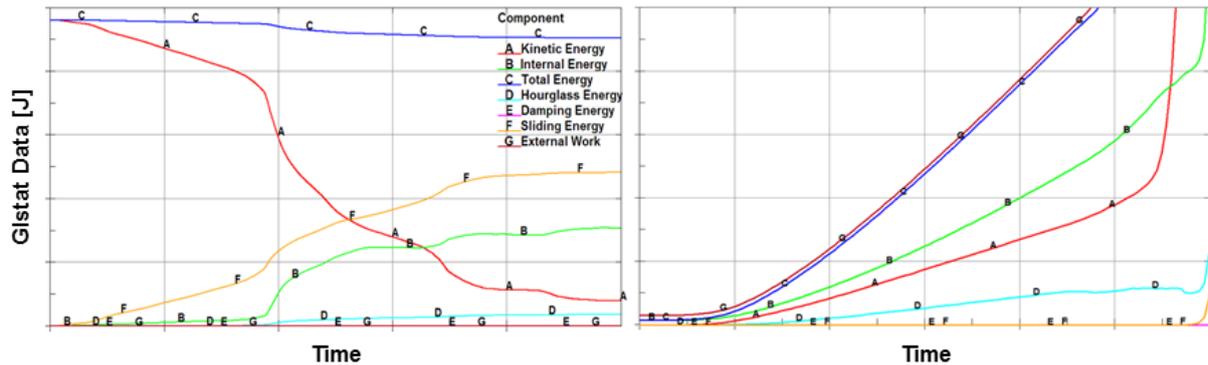


Fig. 4: Energy balance of an impact simulation on the overall model in case of severe damage of the reinforced concrete construction, left: simulation with an airplane model, right: load simulation with a pressure-time function

Fig. 6 exemplary shows in comparison the energy curves of impact simulations using an aircraft model and during loading by means of a pressure-time function in which severe damage to the reinforced concrete construction occurs. In contrast to the simulation with an airplane model, the approach of load areas and a pressure-time function within the load simulation of an aircraft impact is often unrealistic, especially with regard to the energy balance. The damage to the reinforced concrete construction is consequently often overrated. This is particularly due to the fact that the pressure-time function of the effective load acts independently of the construction response and external work force (force * displacement) is executed, which results from the force applied and the deformation. The load virtually has endless energy available. This results in the following aspects:

- The predefined simulation approach of load areas and a pressure-time function does not lead to an energy equilibrium with respect to the kinetic energy of the impacting aircraft.
- The resulting damage to the structure is ultimately energy-controlled (plastic deformation energy). The energy absorbed by the structure up to the state of failure is realistically represented in the model. However, the assumed energy input is not realistic, causing the magnitudes of the calculated damage not to be necessarily adequate for a real aircraft impact.
- If loads become so heavy that the bearing capacity starts to decrease (post-failure behavior), the external work force will increase very strongly due to the disproportionate rise of deformations. In this case, the structure will fail abruptly. Under these circumstances, the determination of a failure mode for exceeding the load capacity (for example, the limit speed of the aircraft) is not possible with the approach of a pressure-time load function.

7 Summary

For proper simulations of the stability and integrity of reinforced concrete structures regarding an aircraft impact, a realistic recording of the affecting loads and the bearing capacities is of crucial importance.

The presented FE modeling was done with ANSYS. The highly nonlinear simulations were performed with LS-DYNA. optiSLang was used for purposes of parameter identification and calibration.

The FE aircraft model was modeled as a shell model and verified with global parameters, like mass distribution, tear-off forces at the wings and engine as well as buckling load of the fuselage. This procedure has already been implemented for the Airbus A320, A340 and A380 aircraft types. The detailed modeling of the reinforced concrete construction was enabled by a volume model (concrete) and beam elements (main steel reinforcement). The procedure considered all materials with suitable elasto-plastic models including damage behavior up to failure mode and verified them on material test data.

Using aircraft impact simulations on the entire system, very plausible damage scenarios could be determined at limit conditions that yielded proper statements regarding the integrity of the reinforced concrete reactor building.

8 Literature

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