Airplane Crash Simulations: Comparison of analyses results with test data

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ABSTRACT

Impact loads are considered in nuclear facility design as the result of the loading effects of certain design basis accidents and design basis threats made up of natural as well as man-made hazards. Also, beyond design basis accidents and threats are considered. Typical missiles include objects caused by tornado winds, aircrafts, war or terrorist activities, dropped objects, turbine fragments and other missiles resulting from failure of rotating equipment and whipping pipes and other objects of failure of pressurized fluid systems.

The aim of the work is to study the potential of tools for numerical simulations to study the local load effects of airplane missiles impacting concrete structures. Two of the leading commercial computer codes for analysis of highly dynamic events, ABAQUS/Explicit and AUTODYN, have been evaluated.

Numerical simulations have been carried out for rigid as well as deformable missiles with the characteristics of airplane engines. The analysis results have been compared with test results from a test program performed in the USA at Sandia National Laboratory and in Japan at Kobori Research Complex and Central Research Institute of the Electric Power industry. Finally, numerical simulations of a large passenger airliner impacting a reactor containment has been carried out using the analysis methodology developed.

INTRODUCTION

Airplane impact effects on concrete structures are traditionally categorized into local and global effects. Local effects are related to effects close to the target structure in the region of the impact and include spalling, penetration, perforation, scabbing and punching. Global effects include overall axial, bending and shear effects in the structural element between the impact region and support points, global stability and vibrations in the structure. The main part of this paper deals with the local effects. For a more comprehensive overview regarding prerequisites and analysis methods for global impact effects see [4]. The focus in this paper will be on medium-speed deformable missiles up to approximately 200 m/s, with mass and stiffness characteristics of typical aircraft engines.

Local damage of impacted concrete structures can be divided into the following effects; spalling of concrete and forming of a crater on the impacted surface, crushing of concrete and penetration into the target, scabbing of the rear face, perforation, and for thinner structures punching out a cone of concrete, see Fig 1.

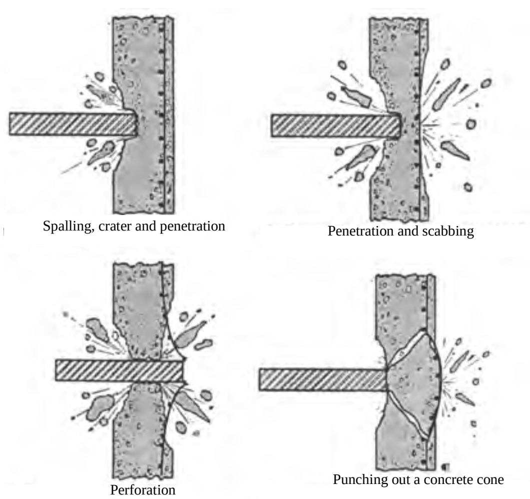
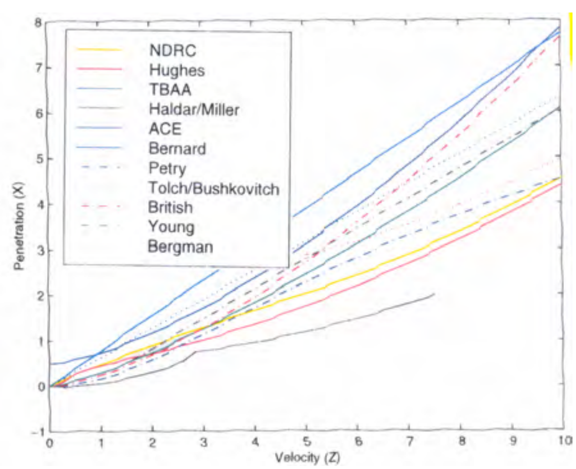


Fig 1, Local damage of impacted concrete structures.



Results differ by a factor of 3.

Fig 2, Comparison of empirical equations predicting penetration depth of rigid missiles impacting concrete slabs (from [9]).

For low impact velocities, the missile will only generate a shallow crater and then bounce back. For higher velocities, the missile will penetrate the target. If the penetration is large enough, the missile will stick. The penetration hole is slightly larger than the missile diameter.

When the missile hits the target, a pressure wave travels through the concrete. This wave is reflected on the rear side giving rise to a tensile wave traveling in the opposite direction. If the tensile stresses generated by this reflected wave are higher than the concrete tensile strength, scabbing occurs on the rear face. For thinner structures, or for heavy missiles with low velocity such as dropped objects, a punching cone failure can occur.

If the missile velocity is high enough, the missile will perforate the target.

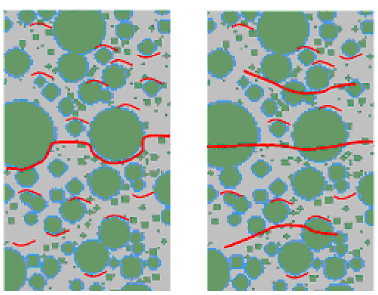
There are numerous empirical equations available based on experiments based on mathematical equations fitting experimental data. The empirical equations will give information about the penetration depth, and also in many cases the risk for scabbing or perforation of the target. Comparing the available empirical equations give at hand that the prediction of penetration depth will differ considerable, up to a factor as large as 2-3, see Figure 2.

Often the empirical equations are used in the range outside the experimental setup, rising uncertainty about the applicability of the results. Also, most of the equations are only valid for rigid missiles, often resulting in a very conservative prediction when applied on deformable missiles. For a more comprehensive review on empirical equations, see [4].

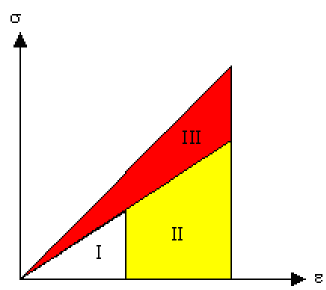
BEHAVIOR OF CONCRETE AT IMPACT

To get complete knowledge of the properties of a material, the properties should optimally be derived from the atomic or molecular level. This is not possible for a non-homogenous material such as concrete, instead the properties normally have to be defined using experiments. Also, to some extent, micro- and meso-models can be used to derive some properties. This information on the behavior of concrete has then to be implemented in macro-models to be used in numerical simulations.

During dynamic loading, the strength and stiffness of concrete as well as the strain capacity, is increased compared to static loading. The fracture plane will then to an increasing extent appear through the aggregates, instead of as for static loading, travel in the cement paste and in the transition zone between the paste and the aggregates. Furthermore, the number of fracture planes will increase as the loading velocity increases. This has been shown in experiments by [8], see Figure 3. In Figure 3, the influence on strength, stiffness and strain capacity due to the alteration of fractural behavior is presented schematically.



Crack path (red lines) for tensile static loads (left) and for dynamical loading (right) based on tests carried out by Zielinski [8].The cracks are shown scheamitacally.



I: Static loading.
II: Effect of multiple cracking during impact.
III: Effect of changed path for single macro-crack during impact.

Fig 3, Crack path for tensile static and dynamical loading respectively (left). Influence on strength, stiffness and strain capacity due to the alteration of fractural behavior (right).

The increase in strength with increasing loading velocity can also be assigned to inertia effects and to viscous effects. The viscous effects are due to the moisture content in the concrete.

During static loading, the concrete compression strength is increased considerably when a confining pressure is present. In the impact zone in front of the missile, a confining pressure from the surrounding concrete can give rise to a considerable increase in compression strength.

The behaviour of concrete depends on the loading rate, i.e. the strain rate. For dynamic loading the strength, deformation capacity and fracture energy change relative to static loading. When concrete is subjected to impact loading, the material strength will increase. This is the case for both compression and tension.

In a uni-axial stress state, there is no residual compression strength when the concrete is crushed. In a multi-axial stress state, however, where the volume of crushed concrete is confined by the surrounding non-destroyed concrete, the failed concrete has a residual strength which will contribute to the resistance. When a missile penetrates a concrete structure, the concrete will be crushed locally in the zone in front of the missile. This concrete will show a residual strength due to the enclosed non-destroyed concrete.

Initially the relationship between hydrostatic pressure and density is linear. At a certain pressure level, however, the relationship between hydrostatic pressure and density becomes non-linear. This is due to micro-cracking and collapse of the pores in the concrete. The concrete is compacted, which is defined as the plastic compaction phase. At very high pressure levels, the concrete is fully compacted and the relationship between the pressure and density again becomes linear.

NUMERICAL SIMULATIONS

Numerical simulations of dynamical non-linear events have been performed with great success over several decades with the help of computer-based methods. The advantage of numerical simulation, and with analytical solutions when they exist, is that knowledge of the physical behavior is gained. Also, several combinations of missiles and targets can be studied, which make it possible to perform sensitivity analyses and parametrical studies. Numerical simulations are studied in detail in this paper.

When studying continuum dynamics, a set of differential equations is established through the application of the principles of conservation of mass, momentum and energy. A constitutive model relates the stress in the material with the strain. Also, for high hydrostatic pressures, an equation of state relating the density and internal energy of the material to the pressure is used. To complete the set of equations, boundary conditions and initial conditions have to be stated.

The set of coupled non-linear equations has been solved exactly only for a very limited number of problems, often with the use of simplifying restrictions. Therefore, to a great extent numerical techniques have to be used.

In this project, two commercial available codes have been evaluated, ABAQUS/Explicit (Hibbit, Karlsson & Sorenson . Inc.) [3] and AUTODYN (Century Dynamics Inc.) [2].

ABAQUS/Explicit is a general finite element code developed to simulate a broad range of dynamic problems, using explicit time integration.

AUTODYN is a so callled “hydrocode”, using a combination of finite difference and finite element methods. This program is also based on explicit time integration techniques.

A hydrocode is according to [1] defined as a computer program which handle the propagation of shock waves and computes velocities, strains, stresses etc., as a function of time and position. Early formulations did not include strength effects. Thus, metals were treated as a fluid, with no viscosity, and the expression “hydrodynamic computer codes” came into being; with time this was shortened to hydrocodes. Nowadays, also strength effects are included in the hydrocodes.

AIRPLANE CRASH SIMULATIONS

Introduction

The main focus in this paper is on numerical simulations of airplane engine missiles impacting concrete slabs. This due to the fact that test results is available, making it possible to compare analysis results with registered test data. These analyses, and comparison with test data, are presented in section “Airplane engine”. Finally, in section “Large passenger airliner” analysis of a large traffic airliner impacting a reactor containment is presented, based on the methodology evaluated in section “Airplane engine”.

Material models

Material models for steel are used to describe the impacting missile as well as reinforcement cast into the concrete slab. An elasto-plastic model with a von Mises yield complemented with a strain hardening description has been used in the analysis.

For the concrete slab, i.e. the impacted target, zones can be identified depending on the local behavior of the structure, and on the type of failure mode dominating that zone, such as compression, tensile or shear failure, or a combined failure mode. The dominating behavior for a specific region can of course vary with time. When applying constitutive models to these types of concrete structures, two main methods can be used.

In the first method each identified zone as above uses the material model most suited for the type of structural behavior and failure mode at hand. The disadvantage with this method is the interactive procedure needed to identify each region and to assign the right material model to each of these regions, taking into consideration the variation in time. Also, care has to be taken in modeling the transition from one region to another.

In the second method a “complete” material model is stated, taking into consideration all relevant phenomena, in order to sufficiently and correctly describe all appropriate behavior and failure modes.

In general, the dynamic response of concrete is complex for this type of highly dynamic impact event. Phenomena that may need to be included are non-linear pressure response, strain and strain-rate hardening, thermal softening, residual strength, damage due to crushing and tensile failure. It is convenient to separate isotropic material description into two independent parts; volumetric stress due to changes in volume (pressure) and deviatoric stress due to changes in shape. Then an equation of state can be specified relating the density and internal energy of the material to the pressure, and a constitutive model relating the stress in the material with the strain.

For each computer code developed for numerical simulation of dynamical events, a number of material models are available, models of general type as well as specially developed models to be used for more complex composite type of materials, for instance concrete. In some codes, there is also a possibility to implement user-defined material models. The material models used for concrete differ for each of the computer codes used, and are presented in connection to the analysis presentation.

Energy considerations

An impact event can basically be described as a system where bodies interact and energies are transformed. The types of energy involved are kinetic energy, elastic (recoverable) energy, plastic (irrecoverable) energy, fracture and thermal energy. The fracture energy is the energy required for creating a certain amount of fracture surface. The total level of energy is always constant in an isolated system. If thermal energy is neglected, the kinetic energy of the missile prior to impact has to be absorbed by mechanisms of the concrete and the reinforcement.

In the case of using artificial viscosity in the numerical simulations, a minor part of the energy will be non-physical absorbed. Also, artificial strain energy will occur associated with constraints used to remove singular modes, zero energy modes or so called hourglass modes, in the four node reduced integration point elements used.

Airplane engine – Test programme for benchmark study

In this paper, numerical simulations are performed to investigate the possibility to predict local damage of concrete slabs impacted by rigid as well as deformable missiles with characteristics of airplane engines. Therefore, a test program performed in Japan at Kobori Research Complex and Central Research Institute of the Electric Power industry has been used as a basis for the simulations. The whole test program, and reported results, is presented in [6] and [7].

The test program included full-scale tests of aircraft engine missiles impacting a concrete slab (this part was performed at Sandia National Laboratory, USA), as well as medium and small-scale tests. In this paper, simulations have been carried out modeling the small-scale tests. In [6] and [7], 44 small-scale tests are reported, using rigid and deformable missiles, for different missile velocities, and for slabs with different thickness and reinforcement ratios. Nine of these tests are used in this study. They are presented below.

For the small-scale tests, the following types of results are available; type of damage to the slab, penetration depth, area of the scabbing and damage to the missiles. For three tests the residual velocity is presented. No information is available of the impact process, such as deceleration of the missile, stresses or strains in the concrete or the rebars, reaction forces etc.

The small-scale tests were executed using a missile launcher. This launcher discharged the flat-nosed missiles against the concrete slabs. With the help of high-speed-framing cameras the missile velocity, the crushing process during impact, the velocity after perforation and the velocity of the scabbed concrete debris from the rear face of the test slab could be registered. The damage to the missile itself was also registered.

Two types of missiles where used, one rigid and one deformable, see Figure 4. Both missiles have the same weight. The deformable missile is made up to have the same structural characteristics as the aircraft engine missile used in the full-scale tests.

The target consists of a reinforced concrete slab as shown in Figure 5. The steel plates shown in the corners of the slab are connected to the supporting frame. The concrete slab is impacted at the center of the slab.

The nine small-scale tests used in the benchmark studies in this report are presented in Table 1 below. The registered damage of some of the test panels are shown graphically in Figure 6.

Table 1, Small-scale tests simulated in this paper

	Slab thickness [mm]	Missile		Damage to test panel			Damage to missile, mode and length after test [mm]
		Type	Velocity [m/s]	Mode[1)]	Dimensions of crater [mm]		
					Front depth	Rear face	
S3	210	Rigid	83	C		Hairline cracks	No damage
S4	210	Rigid	128	S		550x525	No damage
S5	210	Rigid	214	S		660x572	No damage
S9	150	Rigid	97	S	10	520x485	No damage
S10	150	Rigid	141	S	23	440x560	No damage
S11	150	Rigid	198	P	-	660x880	No damage
S17	120	Deformable	101	C	4	Hairline cracks	Buckled 173
S18	120	Deformable	128	S	12	450x340	Buckled 165
S19	120	Deformable	204	P	-	490x1000	Buckled 88

1) C: Penetration, JS: Just scabbing, S: Scabbing, JP: Just perforation, P: Perforation. See Figure 6.

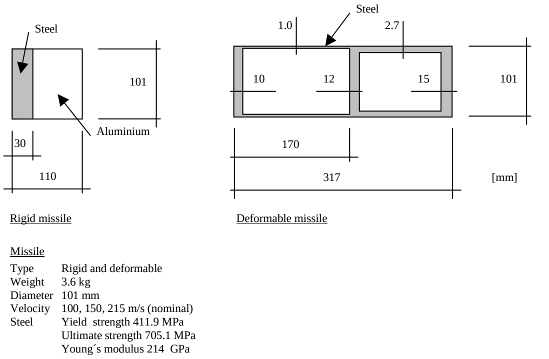


Fig 4, Missiles used in the small-scale tests presented in Sugano (1993).

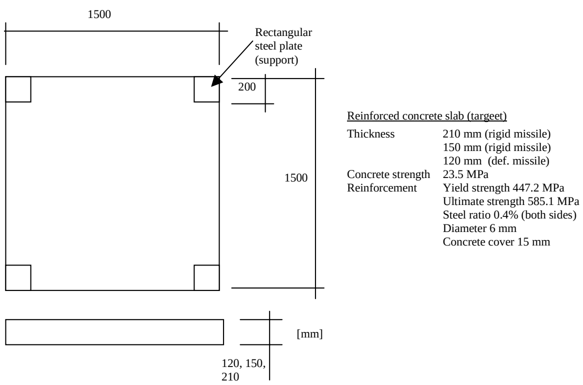


Fig 5, Concrete slabs used in the small-scale tests presented in [6] and [7].

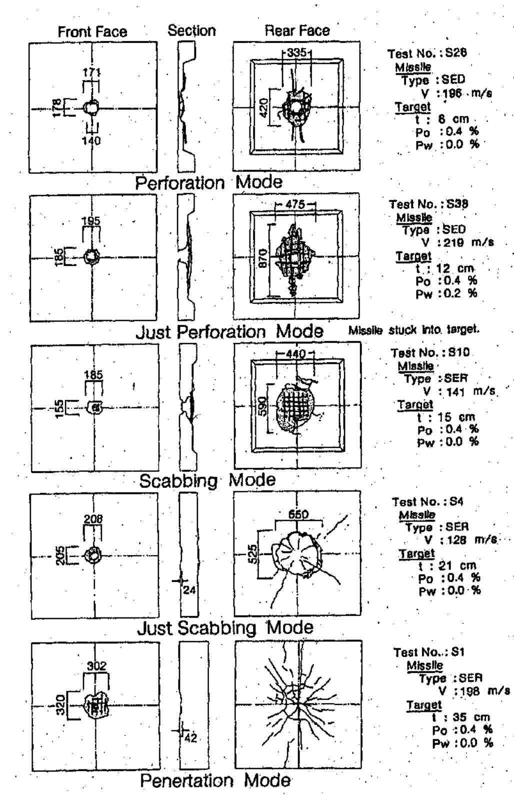


Fig 6, Concrete slabs used in the small-scale tests presented in [6] and [7]).

Airplane engine – Deformable missile

Dynamic events are problems with high complexity and many unknown parameters. The subdivision of one problem into several sub problems, each focusing on a fairly isolated part of the main problem, is sometimes required in order to understand the influence and importance of some of the more significant parameters. Before studying the complete interaction between the deformable missile and the concrete slab, an introductory study is carried out focusing on the deformable missile behavior. The objective of this introductory study is to gather information about the possible modeling problems that may arise when studying the impact of the deformable missile into a rigid surface, thus isolating the problem to the specific missile behavior. An axi-symmetrical continuum model has been used, see Figure 7, with an elasto-plastic material model representing the steel, including the effect of tension-stiffening. The model includes contact definition between the missile and the rigid surface as well as a self-contact definition. The missile is given an initial velocity of 100, 150 or 215 m/s. In Figure 8 the collapse modes for the different velocities achieved in the analysis are compared with registered test data. As can be seen, the behavior of the missile are in good agreement with test data.

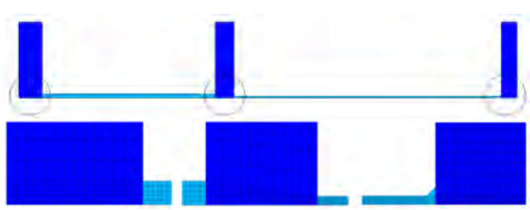


Fig 7, Axi-symmetrical model representing the deformable missile specified in Figure 4.

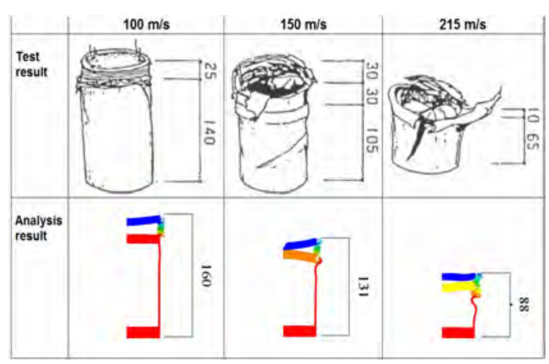


Fig 8, Deformable missile modes achieved in the analysis (lower) are compared with registered test data (upper).

Airplane engine – Impact effects on concrete structures, ABAQUS/Explicit

Three analysis using ABAQUS/Explicit have been performed, corresponding to test S17, S18 and S19 according to Table 1 above, simulating a deformable missile impacting a reinforced concrete slab at three different velocities. ABAQUS/Explicit is a general finite element (FE) code developed to simulate a broad range of dynamic problems, using explicit time integration.

The numerical simulations of the tests have been carried out using the axi-symmetrical model shown in Figure 9. The concrete slab was divided into two material zones. A von Mises material was used in the zone where compressive stresses were assumed to dominate. The remaining part of the slab was modeled with a brittle cracking material, i.e. using the first method described in section “Material models” above. The von Mises material zone was divided into four sub-areas, built up of different von Mises materials. The compressive yield stress of the four von Mises material zones was decreased gradually with distance from the impact zone. The values of the compressive yield stress that were used for the four material zones, were 1.0, 1.5, 2.0 and 2.5 times f_{cc}. During all of the analysis, the same material and input data has been used, except for the variation of missile velocity according to the different tests simulated.

In the first analysis the initial velocity of the missile was set according to test S17, 101 m/s. In Figure 10-11, the calculated penetration depth, missile velocity during impact, and concrete cracking is shown respectively. The analysis resulted in a penetration depth of 3.5–7.5 mm (mean value 5.5 mm). This is quite close to the penetration depth measured in test S17, which was 4 mm.

In the second analysis the initial velocity of the missile was set according to test S18, 128 m/s. In Figure 12-14, the calculated penetration depth, missile velocity during impact, and concrete cracking is shown respectively. The analysis resulted in a penetration depth of 5–20 mm (mean value 12.5 mm). This is quite close to the penetration depth measured in test S18, which was 12 mm.

In the third analysis the initial velocity of the missile was set according to test S19, 204 m/s. In Figure 15-16, the calculated missile velocity during impact, and concrete cracking (missile perforation) is shown respectively. The calculated penetration depth has been left out due to the fact that the missile perforates the slab. The missile perforates the slab. After perforating the slab, the analysis resulted in a missile residual velocity of 40 m/s mm. This is reasonable close to the residual velocity measured in test S19, which were 55 m/s.

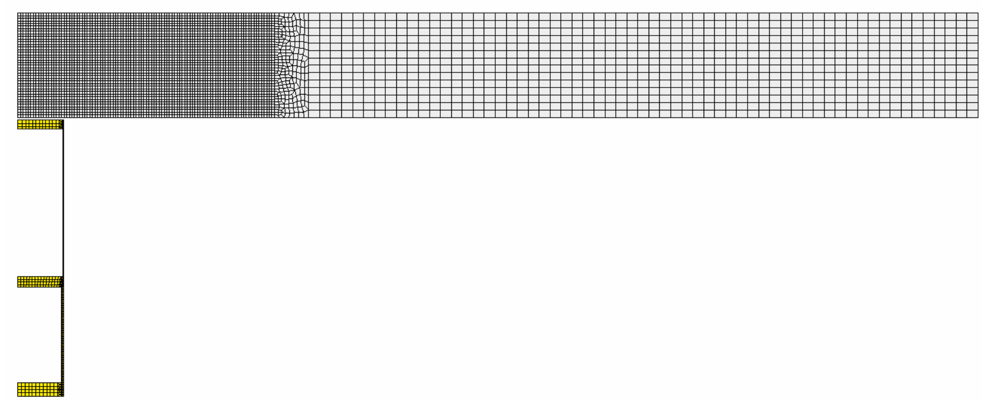


Fig 9, Axi-symmetrical FE model of a deformable missile impacting a reinforced concrete slab used to simulate test S17, S18 and S19 according to Table 1.

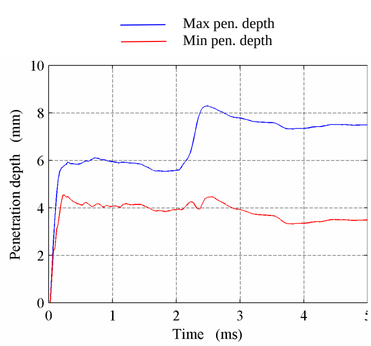


Fig 10, Simulation of test 17: Penetration depth during the impact sequence.

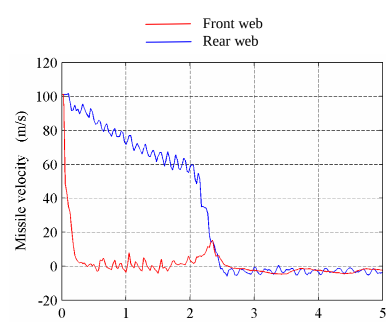


Fig 11, Simulation of test 17: Missile velocity during the impact sequence.

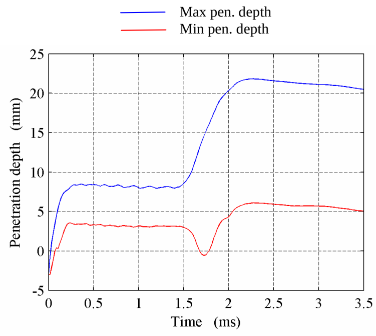


Fig 12, Test 18: Penetration depth during the impact sequence.

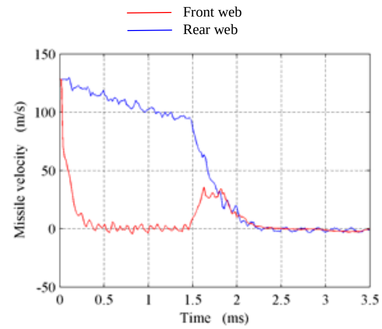


Fig 13, Test 18: Missile velocity during the impact sequence.

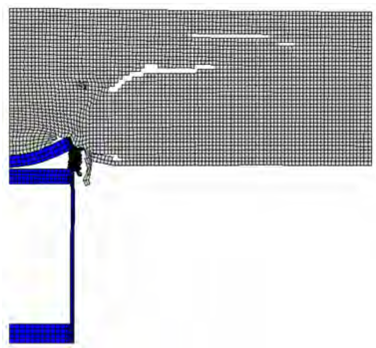


Fig 14, Test 18: Regions with extensive concrete cracking.

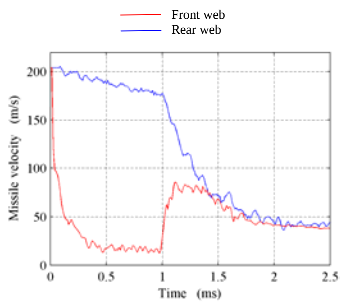


Fig 15, Test 19: Missile velocity at impact sequence.

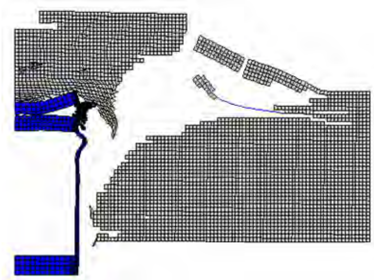


Fig 16, Test 19: Missile perforate the concrete slab.

Airplane engine – Impact effects on concrete structures, AUTODYN

Numerous analyses using AUTODYN has been carried out simulating all nine of the test setups presented in Table 1 above. AUTODYN is a so called "hydrocode", using a combination of finite difference and finite element methods. In Figure 17, typical results from analysis using the so called smooth particle hydrodynamics method are presented. In Table 2 and 3, analysis results are compared with test data. Analyses using a fully 3D-model has also been carried out, see Figure 18.

Table 2, AUTODYN simulations: Penetration depth, modified RHT Concrete model.

No.	Slab thickness [mm]	Missile		Damage to test panel [mm]		Damage predicted by numerical simulation, front depth [mm]	
		Type	Velocity [m/s]	Mode[1)]	Front depth	Finite element models 2D	2D-SPH
S3	210	Rigid	83	C	11	9	
S4	210	Rigid	128	S	24	20	
S5	210	Rigid	214	S	37	51	
S9	150	Rigid	97	S	10	20	18
S10	150	Rigid	141	S	23	36	50
S11	150	Rigid	198	P	-	103	P
S17	120	Deformable	101	C	4	9	
S18	120	Deformable	128	S	12	19	
S19	120	Deformable	204	P	-	P	

1) C = Penetration, JS = Just scabbing, S = Scabbing, JP = Just perforation, P = Perforation. See Figure 6

Table 3, AUTODYN simulations: Scabbing, modified RHT Concrete model.

No.	Slab thickness [mm]	Missile		Damage to test panel [mm]		Damage predicted by numerical simulation, crater size [mm]	
		Type	Velocity [m/s]	Mode[1)]	Crater size [mm]	Finite element models 2D	2D-SPH
S3	210	Rigid	83	C	Hairline cracks	-	
S4	210	Rigid	128	S	550x525	460	
S5	210	Rigid	214	S	660x572	570	
S9	150	Rigid	97	S	520x485	470	500
S10	150	Rigid	141	S	440x560	470	560
S11	150	Rigid	198	P	660x880	690	750
S17	120	Deformable	101	C	Hairline cracks	-	
S18	120	Deformable	128	S	450x340	550	
S19	120	Deformable	204	P	490x1000	550	

AUTODYN is also based on explicit time integration techniques. In the analysis a "complete" material model for the concrete have been used (see section 4.2) including the following features; pressure hardening, strain hardening, strain rate hardening, third invariant dependence for compressive and tensile meridians, damage model for modeling strain softening, equation of state for volumetric compaction and residual strength. The model is named RHT [5], and the tension strength has been complemented to take into consideration also fracture energy and strain rate hardening (modified RHT model).

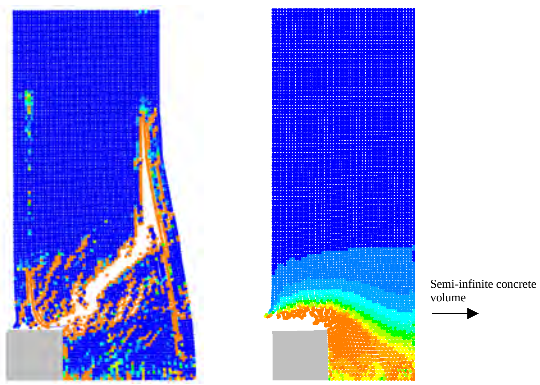


Fig 17, Results using the SPH method in AUTODYN: Thinner structure, punching failure (left). Thicker concrete volume, penetration (right).

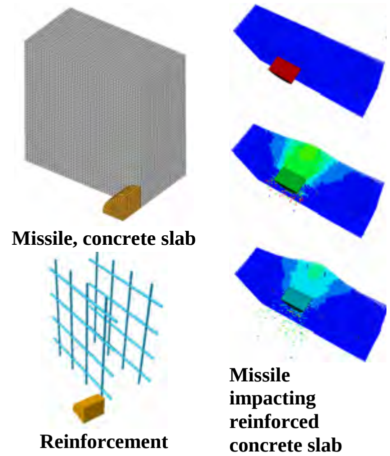


Fig 18, 3D-modeling using the SPH method in AUTODYN.

Large passenger airliner

Utilizing the validated missile impact analysis methodology presented above, analysis has been performed simulating a large passenger airliner impacting a reactor containment. The analysis results are not for the public domain. However, to exemplify the analysis capacity available, results from two governing cases are presented in Figure 19, using non-realistic material parameters. The results shown represent an analysis using a very stiff airplane, i.e. the concrete structure is severely damaged, and an analysis using very stiff concrete, i.e. the airplane is severely damaged.

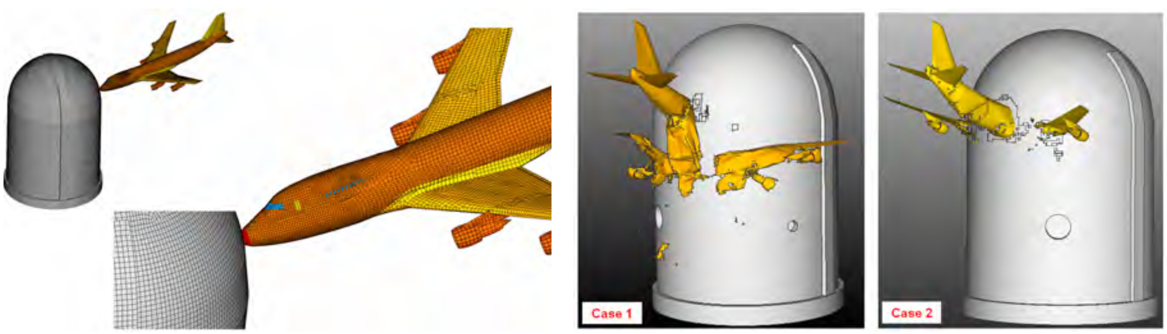


Fig 19, Simulation of airplane impacting a reactor containment, Finite element model (left), analyses results governing cases: stiff concrete (middle), stiff airplane (right).

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