Experimental Investigation and Numerical Analyses of Reinforced Concrete Structures Subjected to External Missile Impact

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External hazards of nuclear facilities include high-energetic missile impact on external protective barriers made of reinforced concrete (RC). Potential sources of such impulsive loading are e.g. accidental as well as malevolent aircraft impact. Despite its low probability, accidental aircraft impact was a relevant loading case for the design of safety relevant building structures of nuclear facilities, while load assumptions have been different in different countries. Since 11.09.2001, also malevolent crashes of larger commercial airplanes are considered. Nowadays, complex analysis codes are frequently used for the assessment of such events. Their accuracy is validated based on impact tests.

This paper focuses on impact tests carried out by the Technical Research Centre of Finland (VTT) in the framework of an international project called IMPACT. Among other partners, GRS participates in IMPACT in order to validate its analysis technique based on the software ANSYS AUTODYN. The test facility and results from tests carried out so far are described. Impacts of "soft" and "hard" missiles on RC structures are considered in this paper. At this, "soft" implies that the missile is deformable relative to the target, while "hard" stands for almost rigid impactor behaviour. Failure mechanisms of RC structures include global effects such as bending vibrations and global cracking. Furthermore, local effects like punching (cone shaped cracking of target below missile), penetration (tunnelling of missile into the target) and perforation of the missile with finite residual velocity are possible. This paper presents results of selected tests and their simulations, each dealing with these different failure mechanisms. Specifications of liquid impact might be of relevance in aircraft crash scenarios. Therefore, some remarks regarding tests with liquid filled missiles are given. Some VTT tests were subject of broad benchmark simulations in the frame of the international activity IRIS ("Improving Robustness Assessment Methodologies for Structures Impacted by Missiles"). The paper gives an overview about the IRIS activity, including comparisons of numerical results obtained from blind and post-test simulations. Finally, the application of the simulation methodology to a generic RC containment structure is outlined. It is concluded, that the relevant mechanical phenomena occurring at high-energetic missile impact on RC structures can be simulated satisfyingly. In simulations of severely loaded concrete dependencies on modelling parameters may emerge. Therefore, parametric numerical studies as well as extended experimental test series are beneficial in order to specify the range of scattering of results.

1 INTRODUCTION

Impact of military and commercial aircrafts is currently still a relevant loading case for design and reassessment of new and existing protective building structures of nuclear facilities. Usually these structures are made of reinforced concrete. Complex numerical methods as well as simplified approaches used for the assessment of such events are validated on the basis of impact tests.

VTT has designed and constructed a facility for impact testing in the 2000s /1/. This test facility (see section 2.1) was designed for testing of concrete walls under impact loading as well as measuring of load-time-functions generated by soft missile impact. The tests have been carried out within different research projects and assignments. VTT also carries out numerical studies using the commercial finite element code ABAQUS. The used modelling methods are validated against the data obtained in the tests. This validation is carried out within the framework of The Finnish Research Programme on Nuclear Power Plant Safety (SAFIR 2014) funded by the state nuclear management fund (VYR) as well as other key organizations in Finland operating in the field of nuclear energy. Since 2005 several organisations have joined an international project, which is now commonly called IMPACT and uses VTTs test facility (see section 2.3). In the framework of the German reactor safety research program sponsored by the German Federal Ministry of Economics and Technology (BMWi), GRS validates its numerical analysis methodology (see section 2.4) for impact assessments. The commercial software ANSYS AUTODYN /2/ is used to simulate selected impact tests. In this context GRS is one of the partners of the IMPACT project. In the framework of IMPACT, numerical benchmark analyses of the tests are carried out among the partners /3/.

Even broader benchmark activities are carried out in the frame of the IRIS activity (see section 2.2 and reference /4/) in which many IMPACT partners participate. This activity is a direct outcome of the IMPACT project. Therefore, this paper pays special attention to tests analysed in the frame of IRIS.

2 EXPERIMENTAL BACKGROUND AND ANALYSIS METHODS

2.1 Impact test facility at VTT

A sketch of the test setup, which is located in an air raid shelter, is shown in Figure 1. The basic idea in its operation is to use air pressure to accelerate the missile to its target speed. Pressure is gradually increased in a pressure accumulator tube (on the left) until it reaches a predefined test-specific value. The pressure accumulator tube is separated from an acceleration tube (in the middle) by a flange with a set of plastic membranes taped on both sides of it. The missile moves on guiding rails which are located above the acceleration tube. When the predetermined value of pressure is achieved, the plastic membranes get punctured and released air pushes a piston, which is located inside the acceleration tube. The missile is then pushed forward by a fin of this piston (see Figure 2). After leaving the launch pad, the missile continues its flight and ultimately hits the target. The piston must not hit the target. Therefore, it is stopped by a piston catcher located behind the muzzle of the acceleration tube. Since the missile travels above the acceleration tube this setup is flexible regarding shape and dimensions of the missile (compare Figure 3). The RC wall to be tested is inserted between two halves of a steel frame resting on wooden planks as shown in Figure 2. The frame itself is supported in horizontal direction against the rock stone by four supports called back pipes. The RC slab may be replaced by a force plate system composed of steel plates and force-transducers. Such a test setup allows measurements of load-time-functions during soft missile impact

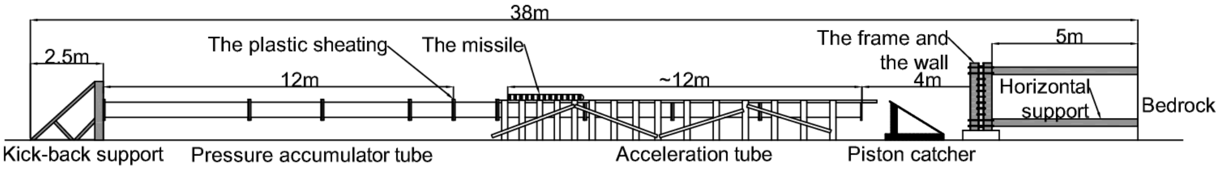


Figure 1: Schematic drawing of the impact test facility at VTT

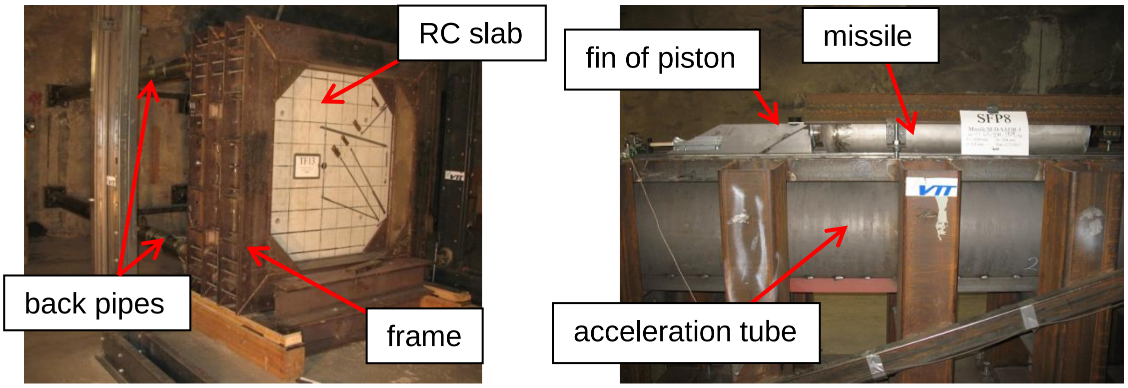


Figure 2: One of the walls inserted in the frame and ready to be tested (left), missile on the launch pad (right)

The test setup has been designed for missiles with a mass up to 100 kg, a diameter between 150 - 400 mm, rectangular RC slabs with edge-lengths of 2.1-2.3 m and thicknesses of up to 250 mm. Different reinforcement arrangements including shear- and bending-reinforcement are tested. The walls can be pre-stressed, if this is desired. Further a steel- liner plate with stiffeners can be attached. The maximum impact velocity that can be reached depends mainly on the combined mass of the missile and the piston. For example, with a missile mass of 50 kg and a piston mass of 52 kg, the maximum velocity which can be achieved with the given setup is 165 m/s.

The actual impact velocity achieved in the tests has been usually within ±2.5 m/s of its calculated target value. The actually realised impact velocity is deduced using the data from laser beams running across the flying path of the missile. The impacts are documented visually using two high shutter speed video cameras taking 1000 frames per second. Usually one of those is taking footage from the front side of the wall in an oblique angle (see Figure 7 and Figure 10) and the other from the backside of the wall (see Figure 9), also in an oblique angle. Footage taken by these high shutter speed cameras is also used as a method of determination of residual velocity of the missile in the punching behaviour tests if the missile perforates the wall.

Forces acting on the supporting back pipes are one of the quantities which are measured during each test. Other instrumentation used in a test depends on the type of the wall to be tested as well as the test type. Commonly it includes at least concrete strains on the front surface of the wall, strains on the selected reinforcement rebars and target slab displacements at selected locations during the test. The estimated error of measurement for displacements is ±2%. Additional information that can be recorded includes forces acting on the pre-stressing tendons if the wall is pre-stressed and strains on a steel liner, if used. The data measured during the tests is recorded on two computers with a sampling frequency of 102.4 kHz. The maximum number of measurement channels is 32 at the moment. The data from the high shutter speed video cameras are recorded on their own memory cards. Final target damage is being recorded. Crack patterns and the areas where concrete was spalled off at the front side and scabbed of at the backside are measured. Further, permanent slab displacements are measured and visualized. After the test one quarter is sawn out of the slab in order to observe damage in the sections. By default, deformation of the missile in terms of its shortening and the number of folds formed during the test are documented.

The test setup can also be used for testing of water filled missiles. In these cases liquid spray front velocities as well as the droplet size distributions of flying droplets can be measured. Further, the range of liquid spray, spatial deposition of fluid and droplet size distributions of droplets fallen to the ground can be determined.

In the near future, some modifications and enhancements of the test facility will be implemented. These modifications will enable reaching of higher impact velocities as well as testing of larger walls (3.5*3.5 m with weight limit of 15 tons). In addition, 3D-structures (wall-floor-wall) will also be tested. In these 3D-structure tests, the main interest lies in propagation and damping of vibration.

2.2 International benchmark activity IRIS

The goal of the IRIS activity ("**I**mproving **R**obustness Assessment Methodologies for Structures **I**mpacted by Missile**s**") is to perform benchmark calculations of selected impact tests with reinforced concrete structures using complex analysis software as well as simplified methods. A general overview is given in reference /4/. This activity is hosted by the WGIAGE (Working Group on Integrity and Ageing of Components) of the CSNI (Committee for the Safety of Nuclear Installations) of OECD (Organisation for Economic Co-operation and Development). The organizational work is done in the frame of the WGIAGE subgroup on concrete structures, at which IRSN (Institut de radioprotection et de sûreté nucléaire, France) and CNSC-CSSN (Canadian Nuclear Safety Commission, Canada) are the leading organizations. Some 28 teams from about 20 different organizations (Technical Safety Organisations (TSOs), regulation authorities, utility companies, vendors of nuclear installations, consulting engineers, international organizations, universities and research institutes) from OECD member states from all over the world participate in the benchmarks. Therefore, this activity is supposed to give a broad overview about the state of the art for this kind of analyses. IRIS is divided in three one-year sub-activities entitled according to the respective years IRIS_2010, IRIS_2012 and IRIS_2014.

In IRIS_2010 the participants were supposed to perform blind pre-test calculations of two tests carried out at the test facility of VTT /7/. One test hereinafter called "IRIS Bending" deals with bending vibration of a RC slab impacted by a soft missile. The "IRIS Punching" test deals with punching failure (cone shaped cracking of target below missile) of a RC slab impacted by a hard missile. In order to ensure repeatability of results and to specify possible experimental scattering the IRIS bending test was repeated twice, while the IRIS punching test was repeated three times. Further, a large scale impact test carried out in Meppen /8/ in the 1970s was considered. This test features combined bending and punching behaviour of a thick RC slab (6.5 x 6 x 0.7 m) impacted by a soft missile (M=1000 kg, v_0=248 ms^{-1}). Despite their age, the Meppen impact tests are still highly regarded reference cases and a problem statement containing detailed descriptions was provided to the IRIS_2010 participants by GRS. More details about the test cases are given in /7/. The idea behind the post-test benchmark of the Meppen case was to calibrate numerical tools to be used in the blind calculation. However, already in post-test calculations non-negligible deviations between simulation results occurred (see references /9/ and /10/).

In the framework of IRIS_2012 the participants had the opportunity to improve their simulation results based on the published test results. Further, additional material test data for concrete characterisation were made available, which could be used to calibrate constitutive laws. As expected, better agreement between numerical simulations and test results can be achieved in post-test simulations. In this context different individual model improvements were presented by partners during the concluding workshop. This paper will focus on the lessons learned by GRS.

Subject of IRIS_2014 will be studies on impact induced vibration propagation and damping in building structures. For this purpose new tests at the enhanced VTT test facility are intended.

2.3 Testing activities within IMPACT projects

Vast majority of the tests executed by VTT have been carried out within joint multinational projects called IMPACT I – III. In these projects, numerous organizations, including GRS and VTT, have combined their efforts to obtain sets of experimental data extensive enough to verify and validate numerical as well as semi-empirical predictive methods and formulas. All the participants contribute to funding with the same amount of money and get all the results obtained from the tests. The tests are decided and designed jointly and executed by VTT. This project is on-going. Phase III has started end of 2012 and its termination is scheduled for end of 2014. In particular, three different test matrices of IMPACT should be mentioned.

The “Bending” matrix is dealing with global bending failure of RC slabs impacted by soft missiles. The IRIS Bending tests belong to this set of tests. Test parameters which were varied within this matrix include:

- Impact velocity
- Missile design (e.g. thin steel or aluminium pipes, liquid filled missile, missiles with wings, missiles with partially filled water tanks (intended)
- Support conditions (one-way simple support and two-way simple support)

Local effects like spalling (ejection of concrete particles from the front face), scabbing (ejection of concrete particles from the back face), penetration (tunnelling into target), punching cone formation and perforation (missile passing the target with finite velocity) are studied in a matrix called “Punching”. This matrix is dealing with hard missile impact on RC slabs. The IRIS Punching tests belong to this set of tests. Test parameters of the punching matrix include:

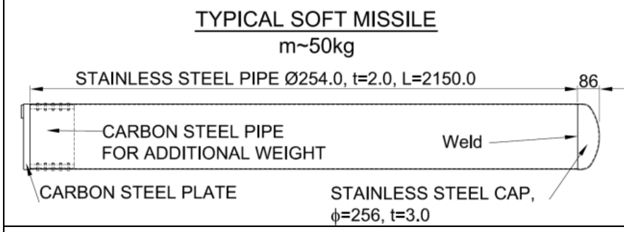
- Impact Velocity
- Type and amount of shear reinforcement
- Slab thickness (intended)
- Amount of bending reinforcement
- Pre-stressing, effects of pre-stressing level and grouted or un-grouted tendons
- Effects of a steel liner attached to the rear face

Recently, a matrix called “Combined Bending and Punching” was initiated. Goal of this matrix is to study the combined appearance of global and local effects in RC slabs impacted by soft missiles made of thin-walled stainless steel pipes. Test parameters of the combined bending and punching matrix include:

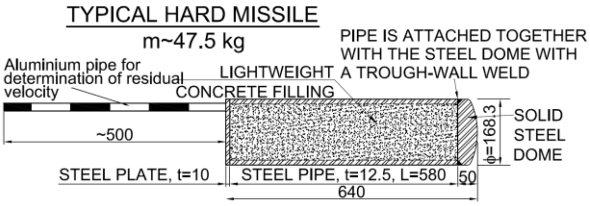
- Missile design and velocity (i.e. load-time-function)
- Amount of shear reinforcement
- Span-width dimensions (intended)

Figure 3 shows sketches of missile designs used for the tests considered in this paper. Experimentally realised parameters of missiles are listed in Table 1. This paper is dealing with the IRIS Punching tests entitled P1-P3, the IRIS Bending tests entitled B1-B2 and other tests belonging to the VTT “Bending” matrix entitled TF11, TF13 and WE1A1.

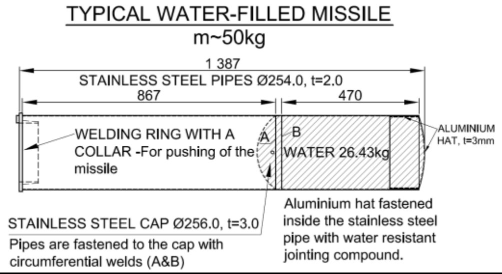
Soft missile used in B1, B2 and TF11



Hard Missile used in P1-P3



Water filled missile used in TF13



Missile with wings used in WE1A1 (~42 kg)

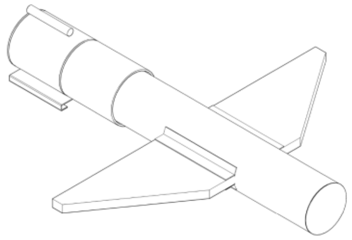


Figure 3: Overview in missile designs used in considered tests

Table 1: Realised test parameters regarding missile in considered tests

Test	Mass [kg]	v_0 [m/s]	Momentum [kNs]	E_{kin} [kJ]	Comments
P1	47.4	136	6.45	438.4	Hard missile used in “VTT Punching” and IRIS Punching tests
P2	47.5	136	6.46	439.3	
P3	47.3	136	6.43	437.4	
B1	50.5	110	5.56	305.5	Soft Missile
B2	50.5	112	5.66	316.7	
TF11 (Dry)	50.5	108	5.45	294.5	
TF13 (Wet)	51.5	111	5.72	317.3	Thin walled steel pipe with water tank (26.5 kg of water, soft missile)
WE1A1 (Wings)	42	123	5.17	317.7	“3D”-missile with wings (soft missile)

Fundamental target properties are given in Table 2. Reinforcement ratios in VTT Bending cases (TF11, TF13 and WE1A1) are slightly larger than those of the IRIS Bending tests (B1 and B2).

Table 2: Dimensions of target slabs of considered tests

Test	Width/ Height [mm]	Thickness [mm]	Reinforcement			
			Bending		Shear	
			Ø of bars [mm]	Ratio [mm^2/m]	Ø of bars [mm]	Ratio [mm^2/m^2]
IRIS Bending	2082	150	6	5.1	6	44.1
IRIS Punching	2100	250	10	8.7	none	none
VTT Bending	2082	150	6	5.65	6	53.55

2.4 Numerical analysis methods

The commercial software ANSYS AUTODYN is used by GRS for structural mechanical problems dealing with impact and blast loading. This code with explicit time integration allows coupling of different numerical solvers in one single model. This is illustrated in Figure 4 for typical impact problem models. The models are dealing with explicit interaction of missile and target by means of contact. Supporting frames are represented by slide bearing boundary conditions. Thin walled deformable structures are represented by shells. Concrete is modelled with solid Lagrange elements while beam elements are used to consider reinforcement. Further, the mesh-free SPH (smoothed particle hydrodynamics) method is available. SPH is suitable to represent bodies undergoing large deformations with changes of their topology. It may be used e.g. for fragmentation of concrete (see Figure 10) or modelling of liquids (see Figure 7 and Figure 14).

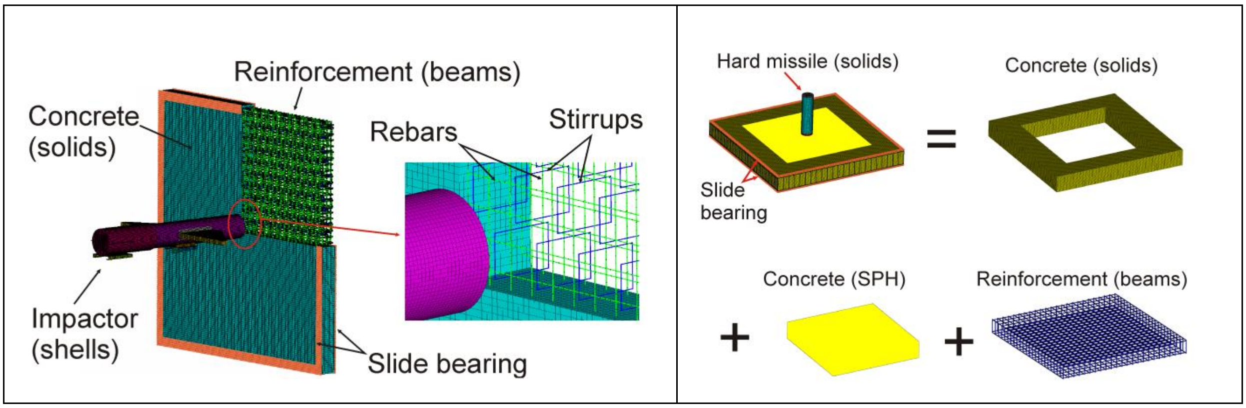


Figure 4: Typical AUTODYN model setups for analyses of impact tests (left WE1A1, right P1-P3)

In simulations dealing with impact loading pronounced material nonlinearities occur. The constitutive laws, especially those used for concrete, must be capable to reproduce the relevant phenomena. In the frame of this work the RHT-concrete model developed by Riedel, Hiermaier and Thoma /5/ was used. This model considers e.g. pressure dependent hardening, strain rate dependent hardening, third-invariant dependency, porosity, damage and residual material strength. Input parameters need to be adjusted to concrete material test data provided by VTT (see reference /6/ for details).

3 ANALYSIS OF SOFT IMPACT

Figure 5 compares displacements of the rear face of the slab at locations of selected sensors. It can be concluded, that both tests succeeded well and repeatability is ensured. Slightly larger displacements are observed in test B2. This may be explained with the slightly higher measured impact velocity and the slightly smaller central offset of the impact point from the slab's centre. Pre-test simulation results overestimate the ultimate slab deflections. In particular the central deflection at sensor D1 is overestimated by a factor of two. Further, the permanent deflections as well as the post impact vibration frequencies are overestimated. This indicates an overestimation of stiffness degradation of the slab due to damage. However, from the safety oriented point of view this conservative result can be assessed as feasible. Obviously the results of post-test simulations are in much better agreement with the test results, even though not in all details. Especially at the sensor D2 located on the diagonal yield line of the slab some deviations regarding ultimate displacement and post impact vibration frequency occur. A sensitivity study exposed that the overestimation of structural damage could be attributed mostly to an inadequate choice of missile material parameters. Figure 5 compares contact forces acting on the target with a load-time-function derived with the so called Riera method /11/. In order to eliminate heavy oscillations in the curve it is useful to consider also the momentum transferred to the target, which is given by time integrals of impact forces. The Riera method is based on conservation of momentum and assumes a perfectly plastic impact. Therefore, its momentum transfer is equal to the initial momentum. Since always some elastic energy is involved, the total momentum transfer is somewhat higher in numerical simulations. For the consideration of strain rate dependent hardening the Cowper-Symonds form /12/ was chosen in the blind analysis. This form seems to overestimate the missile's stiffness, which results in overestimation of average peak load and underestimation of the duration of impact. This results in overestimation of slab displacements. The Johnson-Cook model /13/ utilized in post-test analyses is supposed to yield a more realistic representation of loading. Thus, this model provides better agreement of calculated and measured displacements.

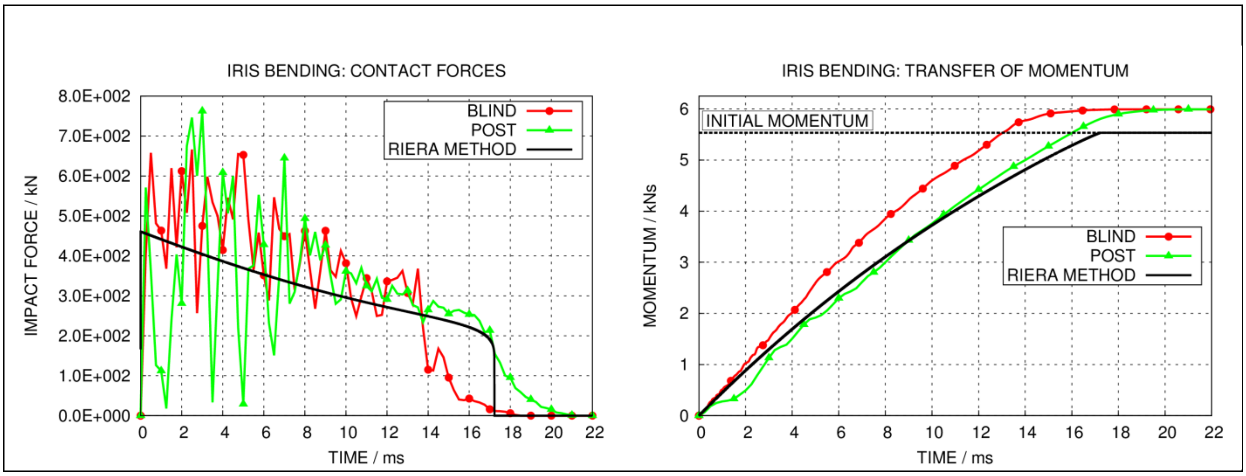


Figure 5: Numerical contact forces and related momentum transfers in IRIS bending test cases in comparison with results derived with the Riera method /11/

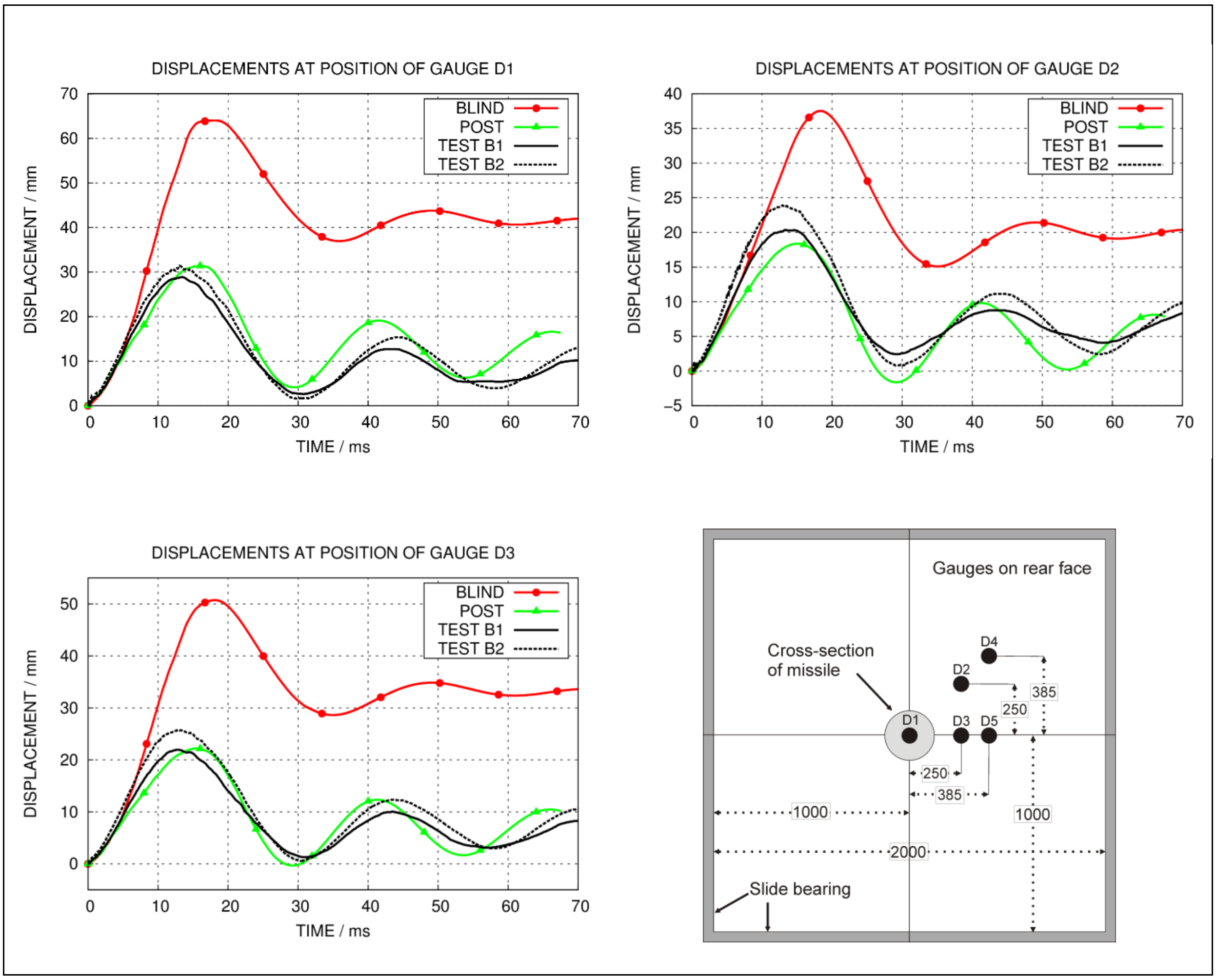


Figure 6: Comparison of measured slab deflections with numerical results of pre- and post-test simulations for IRIS bending test case

From the studies of the IRIS bending case it can be concluded, that deflection of this particular RC slab is quite sensitive to specific features of the load-time-function. This should be pointed out by the comparison of three tests (TF11, TF13 and WE1A1) with three different missile types (see Table 1). Concerning initial momentum and kinetic energy these missiles exhibit quite similar values. However, the related load-time-functions are expected to be quite different. The various missile failure mechanisms are illustrated in Figure 7, which compares missile deformation in test and simulation after 10 ms. The “dry” missile (TF11) is identical with those used in the IRIS Bending cases and shows pronounced buckling of the front part. Due to the water tank incorporated in the nose part, splitting of the pipe followed by almost radial release of water occurs in the “wet” test (TF13). The numerical model uses SPH to consider water infill. Further, a non-cylindrical or “3D” missile with wings has been tested in WE1A1. The goal of these 3D-missiles is not to imitate actual aircraft structures but rather to study the effects of stiffer parts on load-time-function and crushing behaviour as well as their possible local knife-blade effects. This more complex missile structure yields to deformations outside the contact zone. Due to the stiff structure of the wing-box the heavy rear part starts to deform the fuselage behind the wing-box. It is apparent from Figure 7, that the numerical models are capable to describe the failure mechanisms. Concerning the numerical model of the target, the lessons learned from the IRIS benchmark were regarded and only the slightly altered reinforcement ratio was changed in the model. Further, the same target model including numerical mesh and material data was used in this comparative analysis. This allows isolating the effect of load-time-function induced by the different missile types.

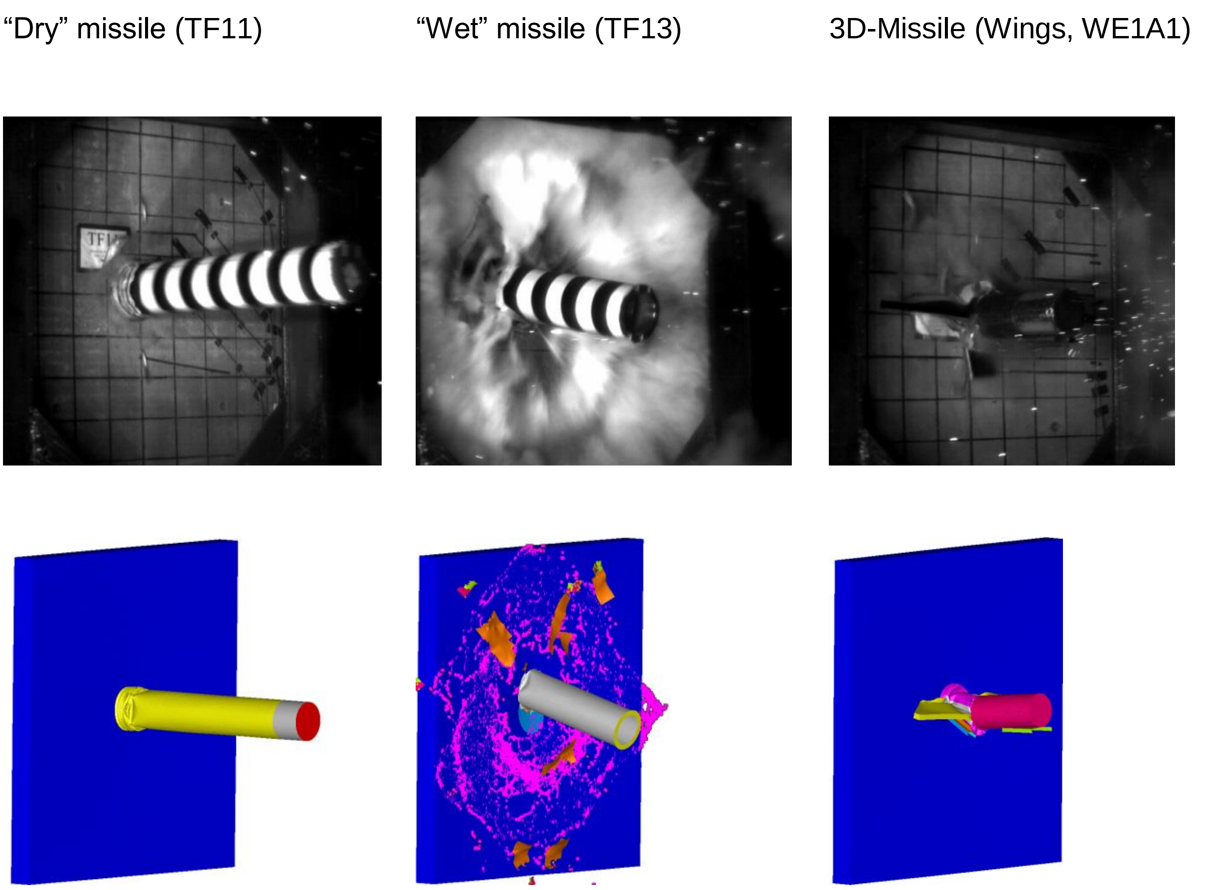


Figure 7: Crushing behaviour of different missile designs in VTT bending test matrix (images after 10 ms)

Numerical contact forces and related momentum transfers to the target are compared in Figure 8. Basically due to the folding mechanism of the thin walled steel pipe in the dry case, impulsive oscillations appear in numerical contact forces. In contrast to that, splitting of the pipe and mass flow of water generate a smoother loading. Features of the loading generated by the missile with wings can be attributed to its construction. Contact between wings and target occurs after about 3 ms and after approximately 9 ms the heavy rear part starts to push the wing-box. It is apparent from the comparison of momentum transfers that the fastest load transfer is realised in the wet case. The momentum transfer curve of wet and dry missile enclose the one of the 3D missile.

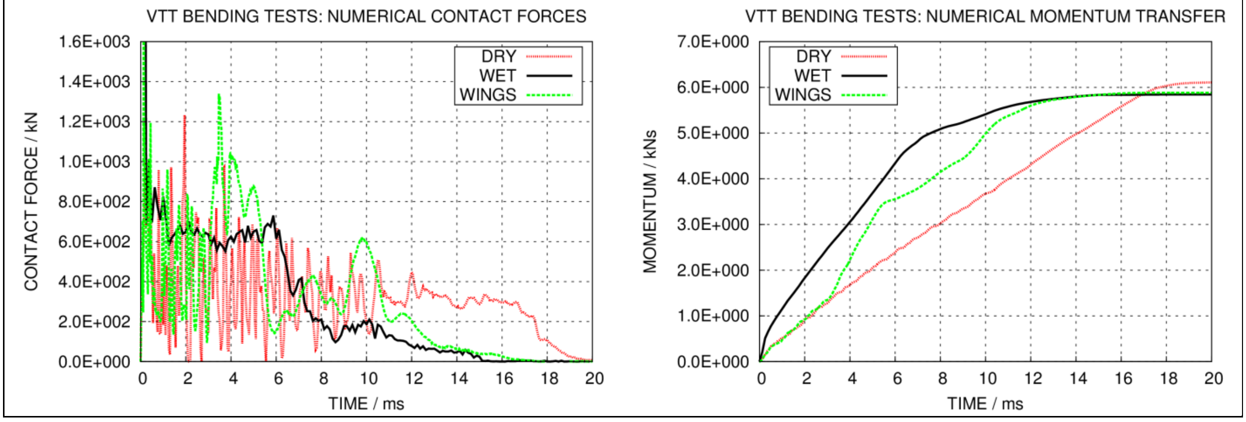


Figure 8: Numerical contact forces and related momentum transfers for different missile designs in VTT bending test matrix

Even though the momentum transfer is almost identical in each case, significant deviations occur regarding target response and damage. Figure 9 compares slab deflections at the location of a certain sensor located on the rear face. In the wet case more than two times larger deflections than in the dry case are observed. These differences can be attributed to differences in the load time function. The maximum deflection in the 3D-missile is enclosed by those of the other two tests. This result is consistent with the consideration of momentum transfers. It can be concluded, that reasonable agreement between test data and numerical simulation results can be achieved. However, some deviations remain, especially regarding post impact vibration frequency.

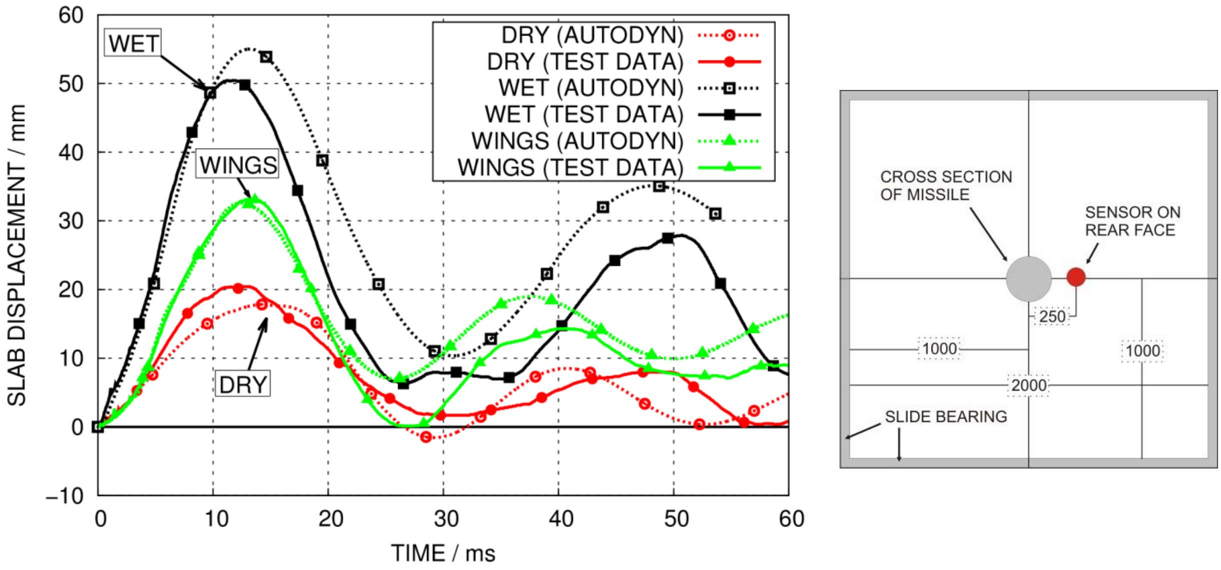


Figure 9: Comparison of measured and calculated slab deflections for different missile designs in VTT bending test matrix

4 ANALYSIS OF HARD IMPACT

Major goal of the IRIS punching tests was to achieve perforation of the slab in order to test whether this process can be simulated by the numerical tools. Therefore, a value of 135 m/s was chosen as intended impact velocity. This value is above the just-perforation velocities v_l predicted by empirical formulas. For example v_l=118 m/s is predicted by the CEA-EDF formula (see /14/) (Commissariat à l'énergie atomique et aux énergies alternatives (CEA)-Électricité de France (EDF)). The test was carried out three times and perforation occurred in all cases. Quite similar results concerning residual missile velocity and dimensions of target damage could be achieved. In blind test calculations a so called Lagrange-model composed of solid- and beam-elements was used. In the impacted area elements become highly distorted, which may result in very small explicit time steps. Therefore, a so-called erosion criterion, used to remove highly distorted elements from the calculation, is required. However, erosion criteria are artificial numerical parameters without any physical foundation. The erosion criterion should be chosen in a way, that major results remain unaffected by its choice. For comparative analyses an additional model with SPH representation of the central concrete part was developed (see also Figure 4). SPH does not require erosion, since the particles are not restricted to a numerical mesh. Further, the calculation is carried out with an almost constant time-step. Major drawbacks of SPH are the additional burden of neighbour-search in each time-step and limited pre-processing capabilities to create the numerical model.

Figure 10 shows high speed camera frames of the slab's front and back face 15 ms after the impact in comparison with deformed models of post-test analyses. At this point in time the perforation process is completed and the missile moves with its residual velocity through the target. Due to debris the missile is not visible on the back face. However, the aluminium tail allows quite accurate measurement of residual missile velocities.

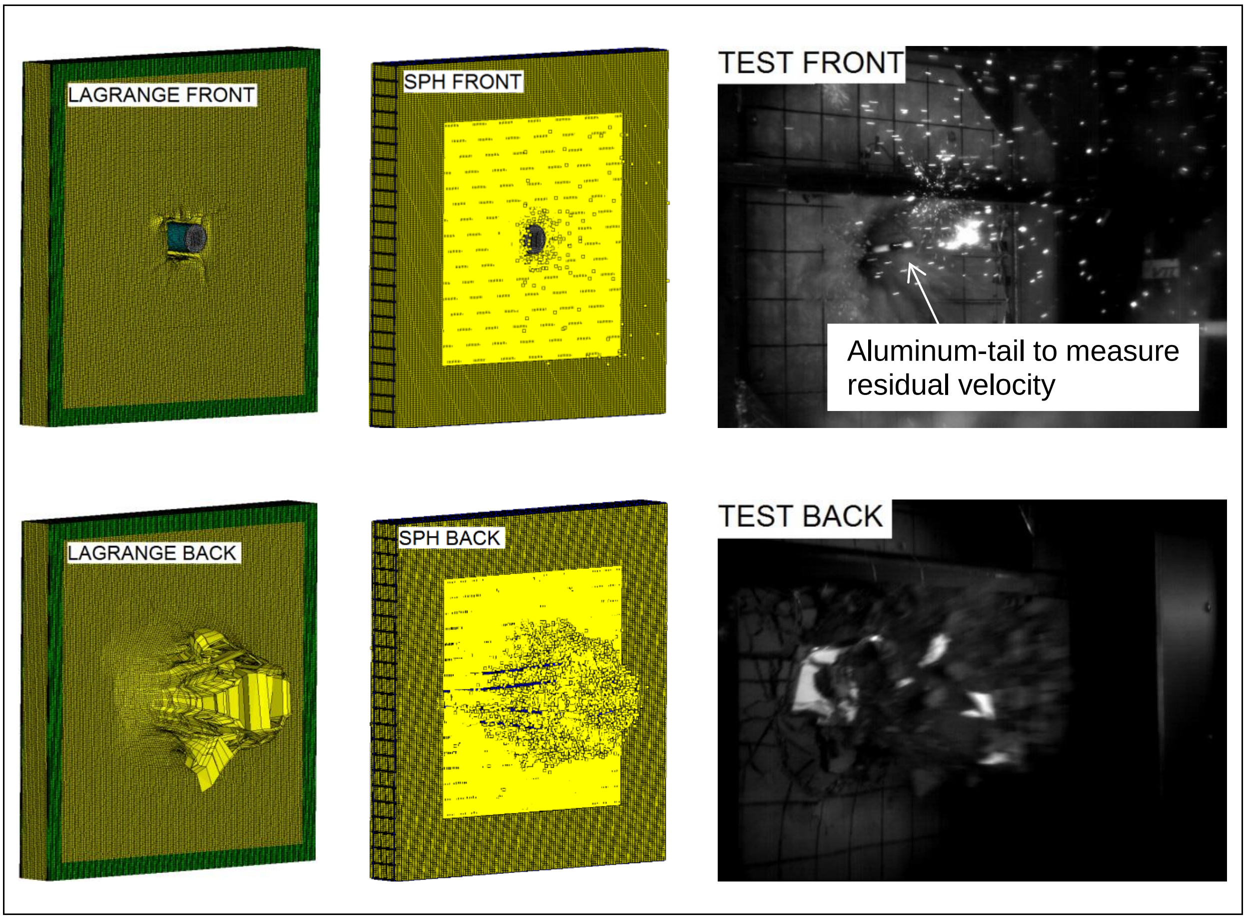


Figure 10: Comparison of missile penetrations after 15 ms for different models with an IRIS punching test

In principle the hard missile perforation process can be divided into a cratering phase followed by a phase with shearing out of a shear punching cone (see /14/). After the test one quarter is sawn out of the slab. Crater and shear cone formation are apparent from the cross sections (see Figure 11). In this particular case a relatively large crater depth of about half of the slab thickness is observed. From the numerically simulated time-histories of missile rear velocities the cratering phase is estimated to last about 1.5 ms (see Figure 11). Results during the cratering phase are almost identical in pre- and post-simulations. Deviations emerge during the shearing out phase. In the blind calculation the missile is continuously slowed down and finally gets stuck. This unphysical behaviour is due to overestimation of membrane action of the back-face reinforcement bars. With regard to through-wall penetration as well as large strains and deformations of reinforcement the blind-simulation results were interpreted as perforation. However, no reliable value for a residual missile velocity could be given. In post-test simulations parameters describing strain rate dependent hardening of reinforcement were altered. Further, the numerical mesh was changed. In the blind model horizontal and vertical reinforcement bars are located in the same plane and connected. For the post-simulations horizontal and vertical bars are separated by a layer of concrete. With these changes the missile is enabled to pass the reinforcement web. Residual velocities for both models are in the scattering range of test results. These were 34±2 m/s in P1, 45±2 m/s in P2 and 36±2 m/s in P3.

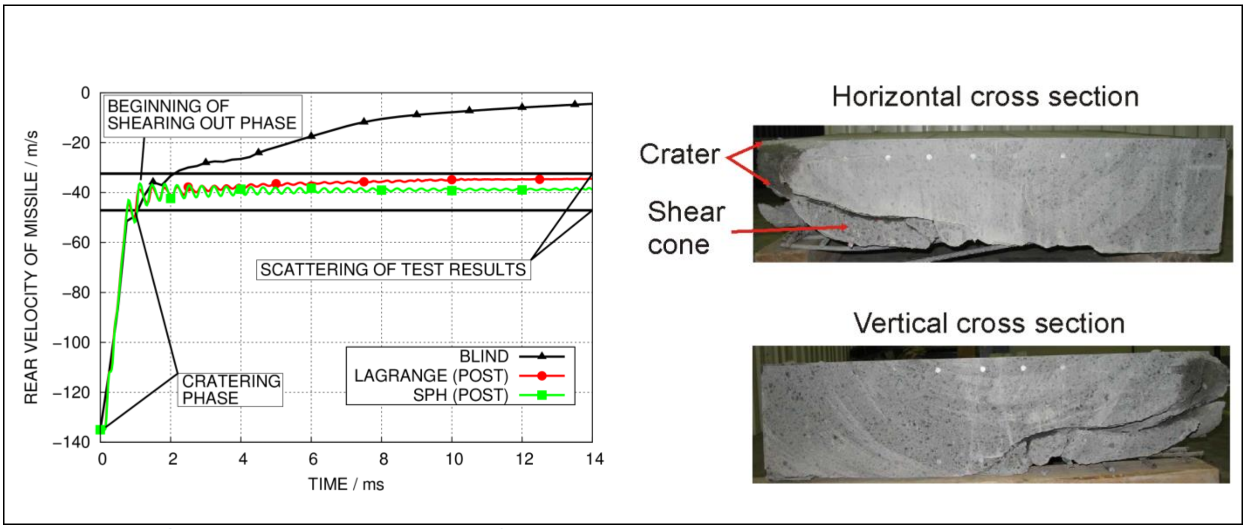


Figure 11: Simulated time histories of the missiles's rear velocity in IRIS punching tests and interpretation based on the slab's cross sections

The RHT model uses a damage parameter describing the degradation of material strength due to damage. A damage parameter equal to one indicates totally destroyed material. Figure 12 shows contour plots of the rear face damage in the final state after perforation for both models in comparison with observations in test P1. Perforation of the slab is obvious in all cases. Some reinforcement bars where sliced and some were spread around the hole made by the missile. Since the horizontal bars are located closer to the surface, the length of scabbed area is somewhat higher in horizontal direction. Thanks to the fact that vertical and horizontal bars are separated in the corresponding mesh setups, the numerical models reproduce this effect as well as the spreading of bars around the hole.

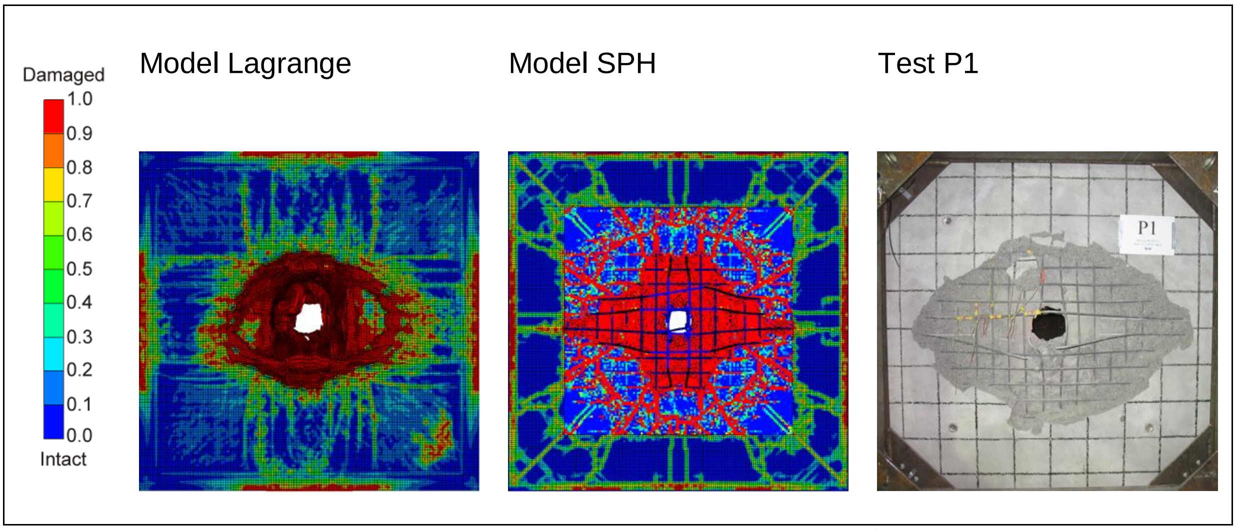
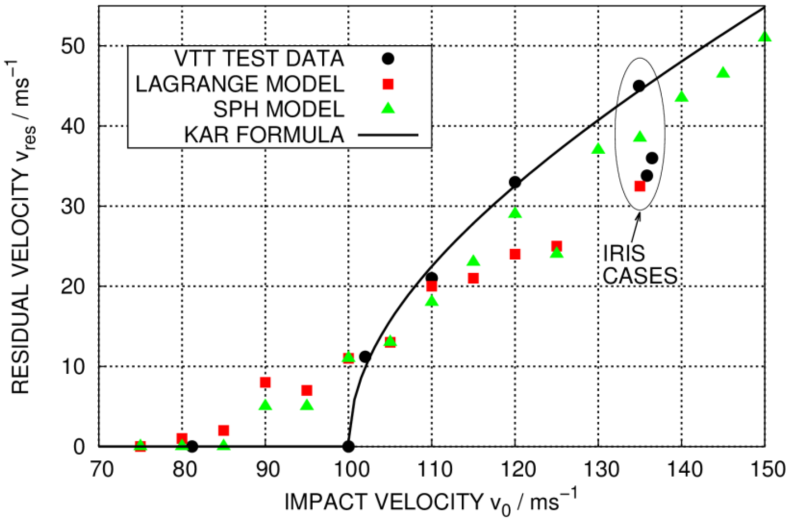


Figure 12: Comparison of ultimate damage contours on the slab's rear face for different models with observed damage in an IRIS punching test slab

Exemplarily the effect of impact velocity is pointed out in Figure 13. In addition to the IRIS punching tests results from five other tests carried out at VTT are shown. Naturally unavoidable scattering regarding concrete material properties occur among these tests. However, the tests seem to match a simple relation between residual velocity and impact velocity given by Kar /15/, which is based on energy conservation. From the test data the ballistic limit velocity or "just-perforation" velocity is assumed to be at about 100 m/s. This value is lower than those predicted by common empirical formula (see /14/). This may be explained by the relatively high compressive strength of about 70 MPa. Such values were not considered at the time most formulas where established and may be out of their validity range. Based on a rough estimation the mass ejected out of the target is about 250 kg. Numerical simulations were carried out using the Lagrange- and SPH model developed for IRIS post-calculations. Quite similar results are obtained from both models. The anticipated ballistic limit velocity seems to be somewhat lower than 100 m/s. The relation between impact velocity and residual velocity is highly nonlinear in the vicinity of the ballistic limit. Therefore, minor differences in parameters may yield in large differences regarding residual velocity and can decide whether perforation occurs or not. In this context more test results close to the ballistic limit would be desirable.



Kar formula /15/:

$$v_{res} = \sqrt{\frac{v_0^2 - v_l^2}{1 + \frac{m_s}{m_M}}}$$

v_0 = Impact velocity

v_l = Ballistic limit velocity

v_{res} = Residual velocity

m_M = Missile mass

m_S = Ejected mass

Figure 13: Relations between impact velocities and residual missile velocities based on a parametric study and VTT punching test matrix results

5 APPLICATION OF ANALYSIS METHODOLOGY TO REAL STRUCTURES

Accidental impact of a F4-Phantom military aircraft has been the traditional design loading in the construction of the latest nuclear power plants in Germany /16/. Therefore, the application of the analysis methodology to real structures is illustrated for this particular loading case. The corresponding design load-time-function is shown in Figure 14. At Sandia National Laboratories (SNL) a well-known full scale impact test has been carried out to record the loads acting during a Phantom F4-Phantom impact (mass=19 t, v_0=215 m/s) /17/. Figure 15 shows some features of a simplified aircraft model based on a geometry given in /18/. Basically the model consists of shells representing fuselage and wings, at which the axial mass distribution of the test is approximated (compare Figure 14). Engines are modelled with solid elements while SPH represents the fuel. Accelerations of the target structure are used to determine the load-time-function. Numerical results and test data agree reasonably well (see Figure 14).

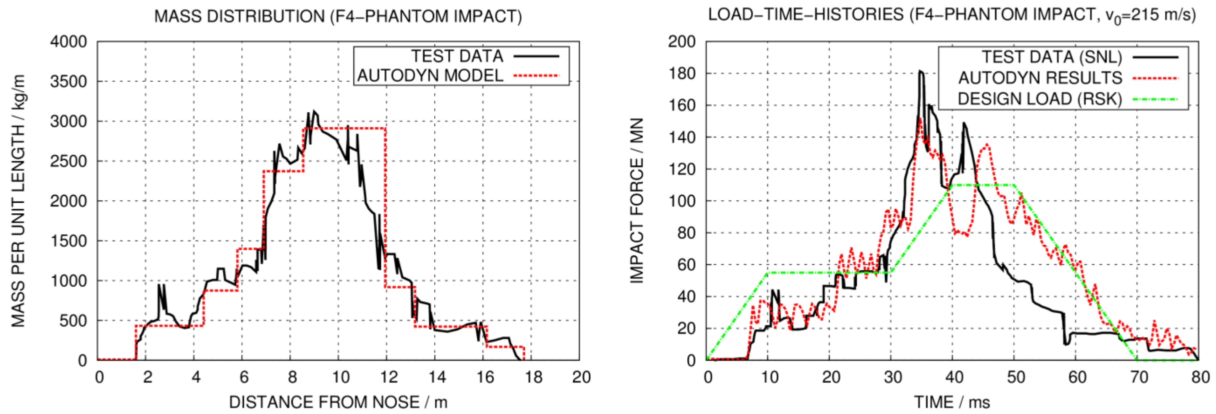


Figure 14: Validation of simplified F4-Phantom model based on the SNL full scale test /17/

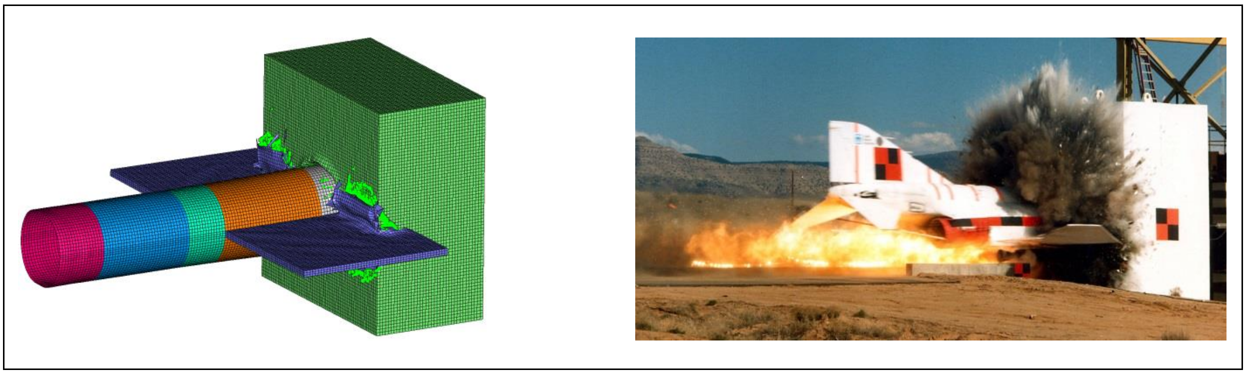


Figure 15: Simplified AUTODYN model in comparison video frame taken during SNL full-scale test /17/

The impact of the validated F4-Phantom model onto a generic nuclear containment is examined in Figure 16. Element sizes in the impacted area are refined. Front and rear face bending reinforcement as well as shear reinforcement is considered in detail in this area. Pronounced concrete damage on front and rear face occurs as a consequence of the impact. Further, failure criteria for rear face bending reinforcement are exceeded in a localised area. However, the impactor remains outside the building structure and a substantial residual bearing capacity is supposed to remain in this loading case.

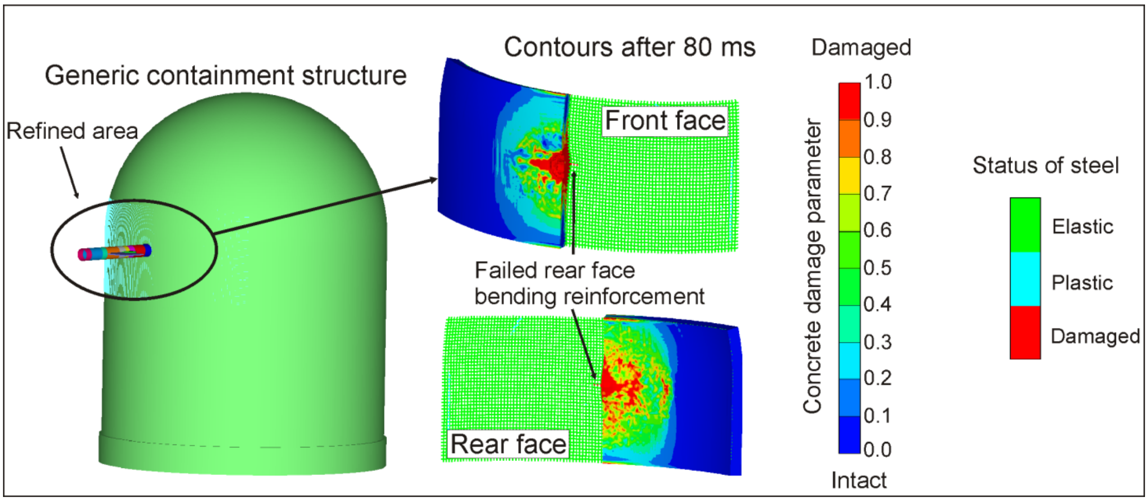


Figure 16: F4-Phantom impact analysis of a generic nuclear containment building structure

6 SUMMARY, CONCLUSION AND OUTLOOK

The Technical Research Centre of Finland VTT has set up a test facility which is designed to study RC structures under impact loading. In this context global bending failure of RC slabs as well as local failure such as punching and perforation is considered. Further, the effect of liquid infill of missiles on loading and target damage is investigated. It is found, that liquid may cause more severe loading and larger resulting bending deflections of the target.

Complex analysis codes such as ANSYS AUTODYN are validated on the basis of these impact tests, for instance in international benchmarks like IRIS. In principle the codes yield satisfying results. However, dependencies on modelling parameters may emerge and broad experience of the user is necessary. Use of complex analysis software for aircraft impact analyses becomes more and more common in the licensing procedures of different countries. Hence, TSOs should be familiar with the accuracy of these methods. The outcome of benchmark activities is beneficial to extend the analysis methodologies to general situations.

Future experimental work will deal with combined bending and punching failure of RC targets as well as vibration propagation and damping in complex structures. Further, the effects of partially liquid filled missiles will be studied. In this context the intended enhancement of

VTTs test facility should be mentioned. It will allow higher impact velocities as well as testing of structures with larger dimensions and weights. Future numerical work of GRS will focus on complex projectiles as well as simulation of real RC structures. Further, conduction of benchmark activities will be continued in the frame of e.g. IMPACT Phase III and IRIS_2014.

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