Interpretation of soft impact medium velocity tests on concrete slabs

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ABSTRACT

Data from impact tests of “soft” missiles on rigid (i.e. thick steel plate) or deformable (i.e. concrete plates) targets are used to validate and calibrate two different numerical methods : a simplified finite difference model developed by IRSN and the fast dynamic finite element model LS-DYNA. The purpose of this work is to predict the loading forces applied by a commercial plane on a nuclear building and the corresponding behavior of the civil work structure. The tests were performed by VTT in Finland.

Two similar tests performed on concrete plates to investigate the scattering of the experimental results have proved to be quite consistent. The repeatability of these first tests then appears to be satisfactory.

Comparing equivalent tests performed either with missiles carrying no fluid, or with missiles loaded with water, shows that loading on targets is more severe when the missiles carry water. The authors think that this result is due to the bouncing of the fluid, which increases the momentum transmitted to the target, as if the impact were not purely “soft” any more but partially “hard”. As a consequence, the assessments concerning the behavior of civil work structures submitted to the impact of a commercial aircraft carrying a significant load of fuel should take into account loading functions higher than those derived by Riera method, depending on the bouncing amount of the fluid on the impacted structure.

Concerning the numerical simulations, the simplified finite difference model developed by IRSN proved to be adapted to the dynamic analysis of a concrete plate behaving like a beam, while the code LSDYNA allows various simulations on any kind of civil structure, with a special effort in choosing the concrete material and mechanical parameters.

Based on the first results of the experimental program, other tests are under way varying the experimental conditions. The data gained from these tests should lead to a better understanding of the phenomena that pilot the interaction between a “soft” missile and a deformable target during an impact.

INTRODUCTION

The analyses of the consequences of an airplane crash on various buildings have developed over the last years. Those studies require a sufficient knowledge of the corresponding loading forces applied by such a missile and of the behavior of the target submitted to that loading. Because of the small amount of available data in that field, an experimental program is carried out by VTT in Finland. As an attempt to add original data to the existing ones, this program consists of impact tests of various missiles on rigid or deformable targets and focuses on deformable missiles impacting reinforced concrete slabs that might undergo not only punching failures, but also flexural modes of plastic deformation. Thus, the program should provide necessary data for the improvement of existing numerical models.

The impact test facility, the missiles and targets, and a general description of the tests performed are shown in another SMIRT 2007 paper, presented by VTT [1].

The French institute IRSN is one of the partners who have joined the experimental program conducted and carried out by VTT. The aim of the present article is to show how the first results of the experimental program are used by IRSN for validating and calibrating some numerical models.

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DESCRIPTION OF TESTS

Missiles

The mass of all the missiles used in the tests below is the same: 50 kg.

The missiles are aluminum pipes, diameter 250 mm and thickness 5 mm (see Figure 1). They are equipped with steel rails for guiding during launching and steel pipe at rear for weight adjustment and propulsion. Some of the missiles are filled with water ("wet missiles", 0.6 m long, 28 kg of water), others are empty ("dry" missiles, 1.5 m long).

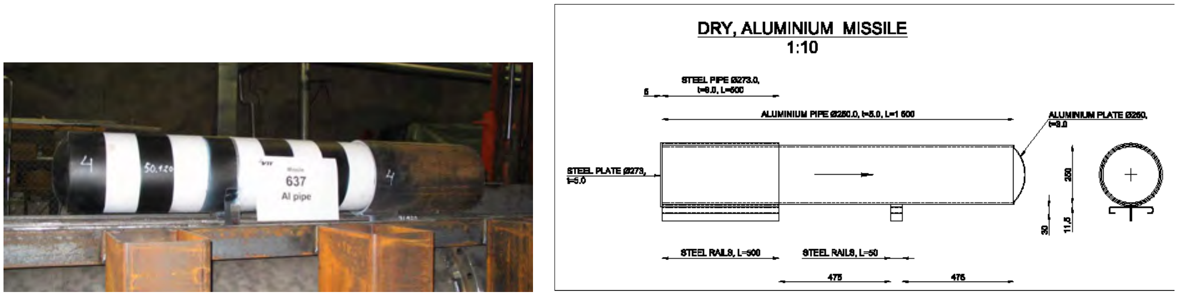


Figure 1 A missile on its launching rail and the corresponding design sketch

Targets

Two kinds of targets are used : a so-called "force plate" acting as a rigid target and reinforced concrete slabs.

Tests analyzed in the present paper

In the present paper, the following 5 tests are analyzed and numerically simulated :

Test number	Type of missile	Mass of missile	Impact velocity of missile	Target
637	dry missile	50.1 kg	110 m/s	"rigid" force plate
642	dry missile	51.5 kg	109 m/s	concrete slab
644	wet missile	51.0 kg	105 m/s	concrete slab
650 (1)	wet missile	50.4 kg	105 m/s	concrete slab
652	wet missile	50.7 kg	104 m/s	"rigid" force plate

(1) Test 650 is a repetition of test 644

IMPACTS OF DEFORMABLE MISSILES ON RIGID TARGETS

In the tests 637 and 652, the missiles (aluminum pipes) are launched on a "force plate" which is a thick steel plate acting as a rigid target and equipped with an instrumentation (strain gauges) that leads to the force-time impact function. This function is a key data for airplane crash analyses. In addition, other strain gauges placed on the 4 steel "back" pipes that support the force plate lead to a force-time function, which is the impact function filtered by the steel structure supporting the force plate. The missile being a cylinder, two numerical models are used to simulate the behavior of the missile during the crash : the Riera method and the fast dynamic finite element model by LS-DYNA. The following results given by both models are compared with experimental data : the length of missile crushed during the impact, the force-time impact function and the momentum transmitted to the target.

Comparison of tests 637 and 652 on "rigid" targets : effect of water filling

The force-time functions recorded in the supporting back pipes during tests 637 and 652 are compared in Figure 2.

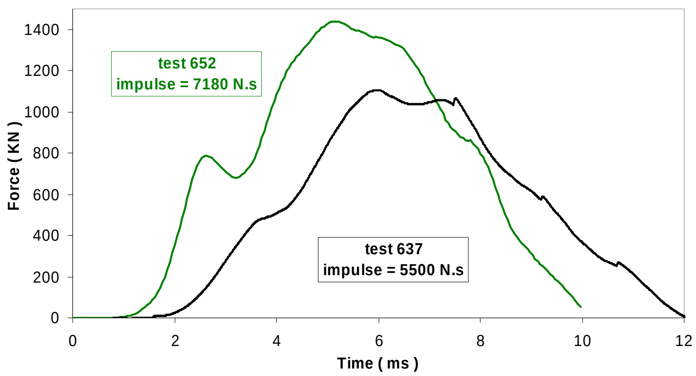


Figure 2. Force measured in back pipes during tests 637 and 652

Figure 3. Camera capture during test 652

Forces and impulse corresponding to test 652, where water reaches 56 % of the mass of the 50 kg missile, are significantly higher than those corresponding to test 637, where the 50 kg missile does not contain water. A rebound of water can clearly be seen from the video and camera captures during test 652 (see Figure 3). This rebound leads to a greater impulse recorded by the target : the impulse recorded during test 652 is 30 % higher than the one of test 637.

Besides, the application of the Riera method to the impacts leads to force-time functions that can be consistent with the "dry" test 637, but not with the "wet" test 652, since the impulse experienced by the target, according to Riera method, is more or less the momentum of the missile. Thus, the Riera method underestimates the loading of the target if the missile carries either a significant part of fluid, or a significant amount of bouncing hard part.

Fast dynamic finite element simulation of test 637

Test 637 is simulated using the LSDYNA code [4] in order to compute the force-time function experienced by the target during the impact and to check the consistency of the missile modelisation.

The whole missile is meshed with 46,165 elements and 45,019 nodes, as shown in Figure 4 below. This fine mesh is necessary to represent the buckling deformations of the missile correctly. It determines the quality of the force-time function. Besides, no symmetry condition is used in the calculation, since a quarter or half model does not enable to represent every buckling modes of the missile. As a consequence, the time–step calculation is small and the duration of the calculation grows in proportion.

The thick steel plate, its supporting steel structure and the 4 steel "back" pipes are modelized (see Figure 5) in order to be close to the exact geometry, and to compare data from the steel structure strain gauges and from the back pipes strain gauges with the calculation results. The model of the whole steel structure provides realistic boundaries conditions. The steel support structure is modelized with an isotropic and kinematic hardening plasticity model including rate effects. So is the missile. It is a very cost effective model provided by LSDYNA for shell elements.

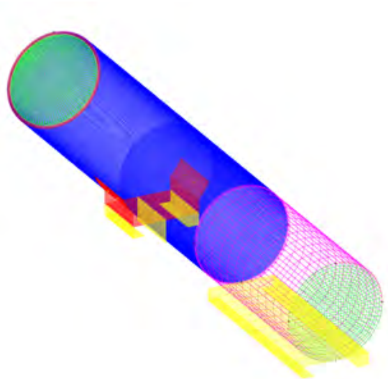


Figure 4. Aluminum missile model

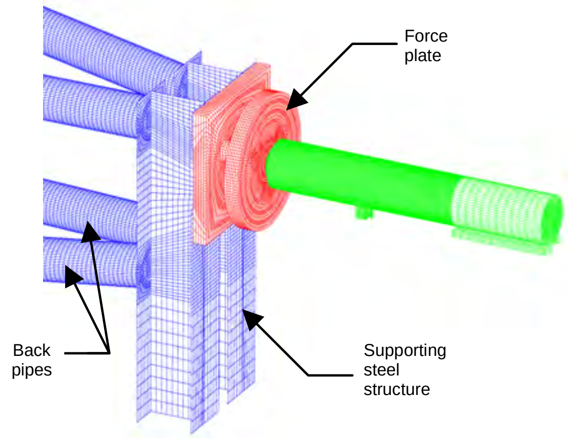


Figure 5. "Force plate" structure model with a missile before impact

The first results of impact simulation on a rigid target are consistent with the test's data since the integration of the force-time impact function given by the Riera method, the back-pipe strain gauges of test 637 and the numerical model are very close. Those integration with respect to time are consistent with the momentum transmitted to the target.

BEHAVIOR OF REINFORCED CONCRETE SLABS UNDER DEFORMABLE MISSILE IMPACT

Reliable predictions of the deflections and of the possible perforations of civil work structures submitted to very energetic impacts are among the main concerns in the safety analysis of nuclear facilities related to external hazards. Because the behavior of the reinforced concrete beyond the elastic limit is complex, the available numerical models must be calibrated, using adapted experimental data.

Therefore, in a second set of tests (namely tests 642, 644 and 650), aluminum pipes are launched on reinforced concrete slabs. All the slabs are the same : one-way rectangular plates, 150 mm thick, simply supported on two opposite edges (2.0 meter long), the two other edges (2.2 meter long) being free. They are reinforced by a square mesh of dia. 8 mm spacing 50 mm. The missile hits the center of the slab. Each of the tests are defined so as to show one simple phenomenon, as follows :

- either a flexural deformation of the slab : a plastic hinge appears along a middle line of the slab which behaves approximately like a beam; in the present experimental conditions this case appears when the momentum of the missile is moderate;
- or the perforation of the slab along a punching cone; this case appears when the momentum of the missile is higher.

The 3 "concrete slab" tests (namely tests 642, 644 and 650) belong to the first type, exhibiting flexural behavior of the slab.

Different numerical simulations are made, using either simplified finite difference model developed by IRSN [3] or the fast dynamic finite element model LS-DYNA [4].

Comparison of tests 642 and 644 on concrete plates : effect of water filling

During tests involving concrete slabs, several measurements are made, including transverse deflections of the slab and strains in rebars. These measurements allow a convenient interpretation of the tests, as shown in the figures below.

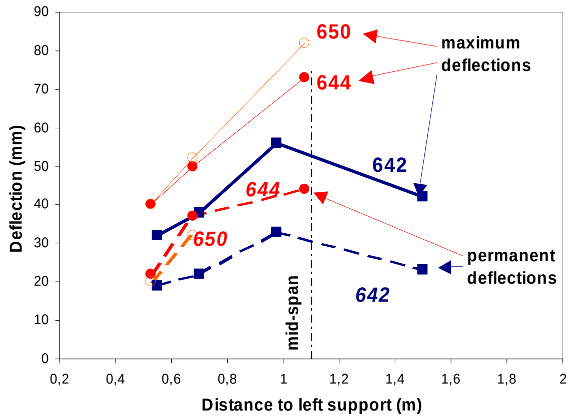


Figure 6. Deflections of the slabs recorded in tests 642, 644 and 650

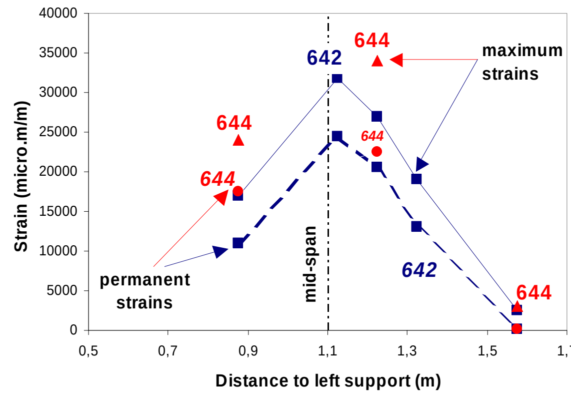


Figure 7. Strains of a rebar in tests 642 and 644

Figures 6 and 7 show that deflections and strains are higher in test 644 (and 650) than in test 642. The difference between these tests is the presence of water in the missile for tests 644 and 650. Thus, as already stated for tests 637 and 652, “wet” missiles appear to be more severe than “dry” ones, the rebound of water leading to a higher impulse on the target.

Simplified simulation of tests 642 and 644 : estimation of the equivalent loading functions

Since the behavior of identical slabs under impacts of identical momentum is not similar (see previous paragraph), there is some interest to estimate the equivalent loadings experienced by the slabs during each test using an appropriate numerical simulation, and to compare those loadings with the loadings derived from the Riera method.

To compare different tests and simulations, we used the time-history of the deflection at mid-span of the concrete slab. This parameter conveniently indicates the main features of the slab: dynamic behavior (frequency, damping) and rigidity, that varies during the elastic and plastic stages of the response.

Using the computer code described in reference [3], the following simulations are carried out :

- a simulation of test 642, for which the loading function is derived from the Riera method, and the momentum is equal to 5520 N.s ; Figure 8 shows that the simulation is in good accordance to the test ;
- a simulation of test 644, for which the loading function is drawn from the Riera method, and the momentum is equal to 5370 N.s ; Figure 8 shows that the simulation and the test do not fit well ;
- a simulation of test 644, for which the loading function is derived from the loading function measured during test 652, and the momentum is equal to 6460 N.s; Figure 8 shows that the simulation and the test are fairly consistent.

The loading functions used in the above simulations are shown in Figure 9.

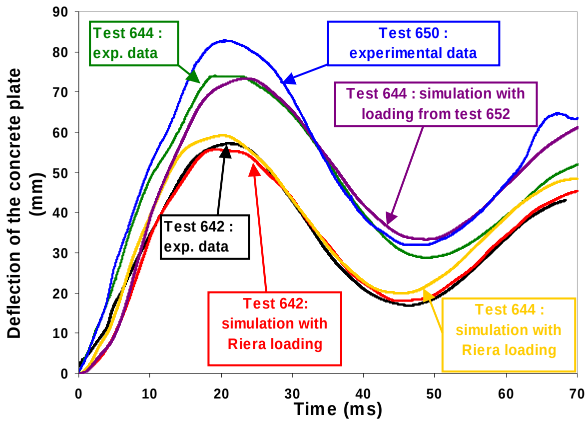


Figure 8 Deflections at mid-span

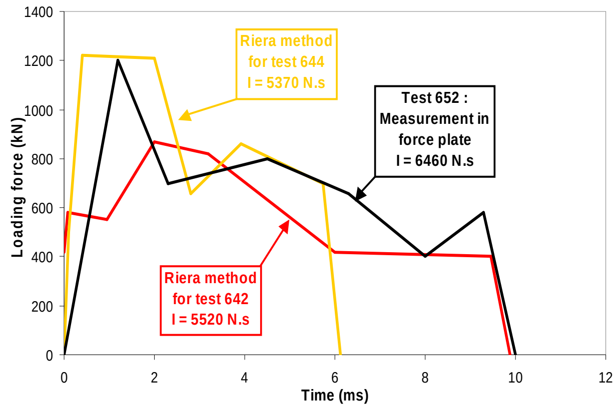


Figure 9 Loading functions used in the simulations

From Figures 8 and 9, the experimental results of impact tests of missiles loaded with water ("wet" missiles) on concrete slabs demonstrate that "wet" missiles are more severe that the equivalent "dry" ones, because they transfer higher momentum to the target.

This conclusion concerning tests on concrete slabs is similar to the one already drawn from rigid plate tests (see the previous paragraph "Comparison of tests 642 and 644 : effect of water filling"). As a consequence, the assessments concerning the behavior of civil structures submitted to the impact of a commercial aircraft carrying a significant load of fuel should take into account loading functions higher than those derived by the Riera method, because of the bouncing of the fluid on the impacted structure.

Comparison of tests 644 and 650 on concrete plates : repeatability of the tests

In order to investigate the experimental scattering of tests results, test 650 is a repetition of test 644.

The main results of both tests are compared below :

- both missiles undergo the same destruction pattern, the aluminum being torn into small (about 0.20 m) pieces;
- targets present the same deformation pattern, a vertical plastic hinge appearing at mid span of the slabs;
- the maximum and permanent deflections measured on both slabs are in good agreement, as shown in Figure 6.

The repeatability of tests on concrete plates then appears to be satisfactory.

Fast dynamic finite element simulation of test 642

The concrete slab (208 624 solid elements and 228 242 nodes, see Figure 10 below) is modelized with the LSDYNA Winfrith concrete smeared crack material which is implemented in the 8-node single integration point continuum elements developed by Broadhouse and Neilson and validated against experimental data. With the LSDYNA Winfrith material, a regular mesh is required. This material can be used in case of moderate impulse causing cracking and flexions of the slab. The main concrete mechanical parameters are the uniaxial compressive and tensile strength and the fracture energy, available

from tests on concrete samples. The LSDYNA Krieg material (Soil and Foam model) which is easier to use and to calibrate proved to be more robust and reliable. This material will also be used and compared to the Winfrith material.
Rebars are modelized with 22 404 truss elements whose nodes are confused with the concrete nodes; the coupling interaction between a slave Lagrangian geometric entity and a master one proved not to be available in LSDYNA 970 Version.
Quite a few tests on simplified models have been carried out to assess the sensitivity of the main results to concrete models and to concrete mechanical parameters. Eventually, the best numerical model for the VTT impacts was chosen.

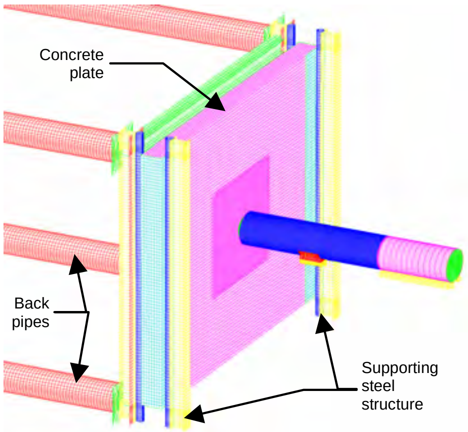


Figure 10. Model for test 642 : concrete slab, steel supporting structure, and missile

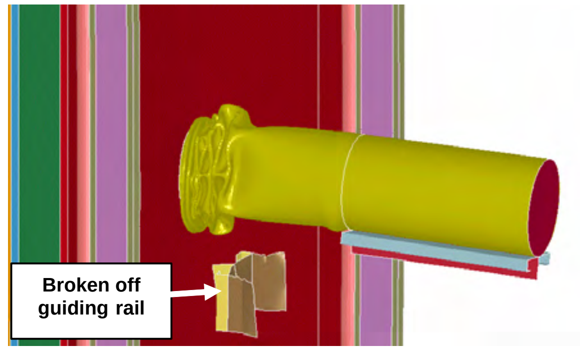
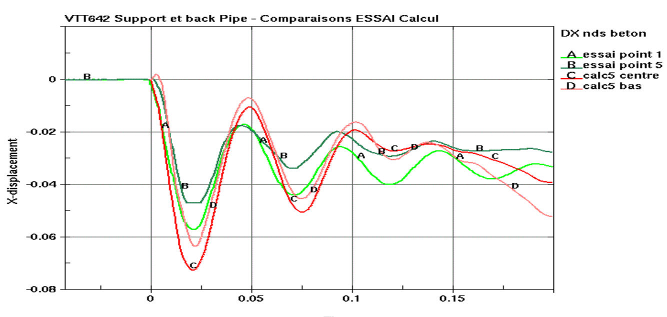


Figure 11. Simulation of test 642 : deformation of the missile impacting the concrete slab

The fine mesh of the missile and the concrete material involve a long duration of calculation. Several types of contact laws must be used to modelize interaction between the concrete and the missile, the concrete and the supporting structure, the missile and the guiding rail.

In the case of a concrete slab subjected to a moderate velocity impact (VTT test 642, see Figures 10 and 11), the order of magnitude and the frequency of the concrete oscillations, the residual deformations of the slab and the missile crushed length resulting from numerical simulation are consistent with the experimental data, as shown in Figure 12.



NOTA. Point 1 is the impacted central point of slab and point 5 is the mid-span lower point.

Figure 12. Test 642. Deflection at mid-span of the concrete plate.
Measured (green color) and calculated (red and orange color) time histories

The cases of high velocity impact, and missile loaded with water, will be studied later using LSDYNA. An erosion capability must be included into the Winfrith material when simulating concrete structures subjected to impulsive loads. If not, the LSDYNA "mat_concrete_material" (number 72) might be used.

CONCLUSIONS

In order to improve the assessment the consequences of an airplane crash on nuclear civil structures, the authors have analyzed and simulated numerically a few impact tests performed by VTT in Finland.

In that process, two different numerical methods were used, namely a simplified finite difference model developed by IRSN [3] and the fast dynamic finite element model LS-DYNA [4].

The first analysis of soft impact tests in which the targets are either a rigid steel plate, or a reinforced concrete plate, leads to the findings below.

The two similar tests performed on concrete plates, to investigate the scattering of the experimental results, have proved to be quite consistent. The repeatability of the tests then appears to be satisfactory.

Comparing equivalent tests performed either with missiles carrying no fluid, or with missiles loaded with water, shows that the loading of the target is more severe when the missile carries water. The authors think that this result comes from the bouncing of the fluid on the target, which increases the momentum applied to the target, as if the impact were not purely "soft" any more, but partially "hard". As a consequence, the assessments concerning the behavior of civil work structures submitted to the impact of a commercial aircraft carrying a significant load of fuel should take into account loading functions higher than those derived by Riera method, because of the bouncing of the fluid on the impacted structure.

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Based on the first results of the experimental program, other tests are under way, varying the experimental conditions. The data gained from those tests should lead to a better understanding of the phenomena that lead the interaction between a "soft" missile and a deformable target during an impact.

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