Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Special session: History and State of the Art for Impact Analysis

HISTORICAL REVIEW OF IMPACT TESTS CARRIED OUT AT VTT

Ari Vepsä[1], Kim Calonius[2], Alexis Fedoroff[2], Arja Saarenheimo[3]

[1] Senior Scientist, VTT Technical Research Centre of Finland, Espoo, Finland (Ari.Vepsa@vtt.fi)
[2] Senior Scientist, VTT Technical Research Centre of Finland, Espoo, Finland
[3] Research Team Leader, VTT Technical Research Centre of Finland, Espoo, Finland

ABSTRACT

9/11 terrorist attacks against WTC-towers caused many things. For example, it gave impetus for construction of VTT's impact testing facility. 288 impact tests has been carried in it since its inauguration in 2003. Majority of the tests have been carried out in jointly funded multinational testing projects Impact I – Impact IV. In addition, a small selection of tests has been carried out within Finnish national research projects as well as in assignment works. The tests have resulted wealth of important data and information regarding different types of impacts. Large part of the information has been disseminated on different scientific forums like, for example, SMiRT conferences. With rising interest in scale effect, a new testing apparatus is being built which enables testing of larger samples with heavier projectiles and higher velocities.

INTRODUCTION

An aircraft impact against nuclear power plant became relevant research topic again after 9/11 terrorist attacks against WTC-towers. As part of this new wave of interest, VTT Technical research centre of Finland built its own impact testing facility in 2003 with the aim to study the phenomena arising during projectile impacts against reinforced concrete structures. With the facility and activities presented in multiple conferences, numerous other nuclear power related organizations shoved interest in it and wanted to join in. With the aid of numerous funding parties, 288 impact tests have been carried out with the VTT test facility so far. 141 tests have been carried out with reinforced concrete (rc) targets and the rest with projectiles only.

Most of the tests have been carried out in jointly funded projects Impact I - IV. The first such project started in 2005. It was clear from the beginning that the focus of the activities in the projects will be on studying the phenomena that arise in such impacts in contracts to studying the impact behaviour of specific structural solutions. The underlying principle was that every participating organization contributes to funding with equal amount of money. Test planning was carried out collectively with one participant organization assigned with the main planning responsibility for each test type. The results of all the tests were shared among the participants. In addition to VTT, the organizations that have participated at least one of the projects are Candu Energy (Canada), CNSC (Canada), EDF (France), ENSI (Switzerland), Fortum (Finland), GRS (Germany), IRSN (France), Kajima Co. (Japan), NRC (USA), ONR (Great Britain) and TVO (Finland). In addition, consults of the participating organizations like Basler & Hoffman and Stangenberg und Partner Ingenieur - GmbH (SPI) have actively contributed to planning of the tests as well as analysis of the results. Special acknowledgement goes to STUK (Finland), who's representative has acted as the chairman of the project group meetings from the beginning of the activities.

IRIS 2010 (OECD NEA, 2012) and IRIS 3 (Hervé-Secourgeon et al., 2016) were OECD/NEA benchmark exercises studying how reliably existing computational tools can simulate the phenomena arising in an aircraft crash against a reinforced concrete structure. Three punching behaviour, two bending behaviour and three vibration propagation tests were carried out within the exercises at VTT premises. Participating organizations submitted their blind simulation results for selected test parameters and provided results were then compared against the measured ones.

Alongside international testing campaigns, VTT has also made selected tests within the framework of Finnish national SAFIR research programme. These tests have concentrated on punching and combined bending and punching behaviour of target slabs as well as behaviour of liquid (water) as it spreads out of a reputing projectile, emulating the fuel tank, during an impact.

VTT IMPACT TEST BED

The VTT impact test bed is shown in Figures 1 and 2. Its operating principle is to use compressed air (in yellow tube) to drive the projectile towards the target. A steel piston, which function is to push the projectile with its fin, is located inside an acceleration tube and is stopped before it hits the target. The projectile, located on the rails on top of the tube, impacts the target. Target’s response to the impact is measured with suitable sensors. When using square slabs as targets, they are clinched between two halves of a steel frame, connected to the facility wall with steel pipes. Three dimensional targets, like the one used in IRIS 3 benchmark and shown in figure 1, can be tested using special supports.

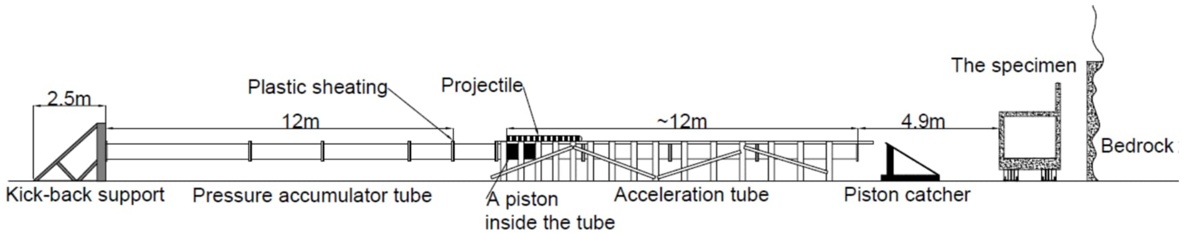

Figure 1. VTT impact test bed, gen 1.

Figure 2. VTT impact test bed, gen1.

TEST TYPES AND THE PHENOMENA EMULATED IN THEM

Different phenomena that arise in an aircraft impact has been generally studied in separate tests. These phenomena include

- impact force generation of a soft projectile,
- local punching of the targets when subjected to hard projectile impacts,
- global bending of the targets when impacted with a soft projectile like an aircraft fuselage,
- combined bending and punching of the targets subjected to semi-soft projectiles,
- load magnification due to fuel tanks and spreading of fuel (emulated with water for safety reasons),
- vibration of the structures when subjected to impact and the force that is generated by the impacting projectile,
- possible "knife effect" of winged projectiles and
- the effect of the inclination angle on the results of the punching and bending behaviour impact (Figure 3).

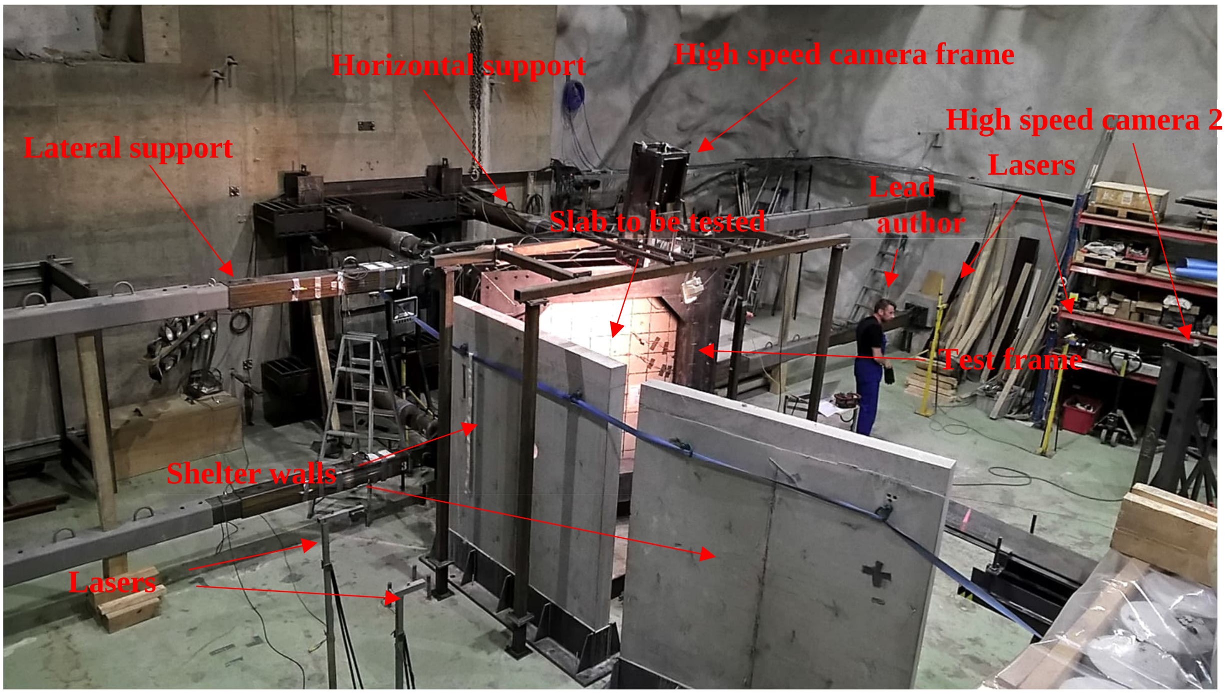

Figure 3. Recent test set-up realized in an IMPACT IV/NEREID project test of inclined impact.

Most of the tested targets have been planar slabs with typical in-plane dimensions of 2.1 meters by 2.1 meters. The slabs have been simply supported either 1-way or 2-way with the span width being 2.0 or 2.2 meters. On few occasions the projectiles have been shot against a steel plate with a set of load cells attached on the rear surface (force plate set up) as shown on the left in Figure 4 or a more complicated 3D-structure as shown on the right in the figure.

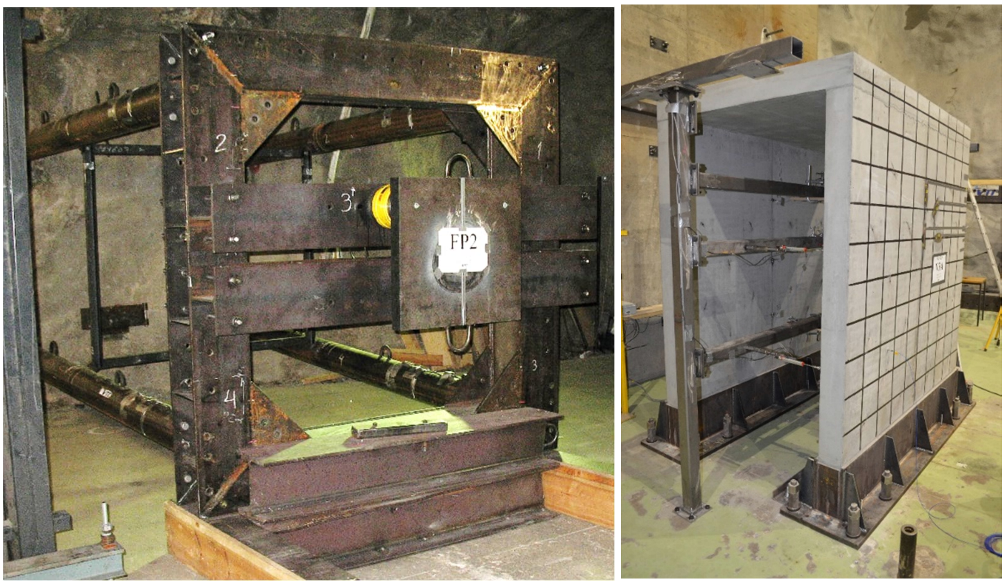

Figure 4. Left: Force plate test set-up. Right: Vibration test mock-up V3 (right) ready to be tested.

Instrumentation

Due to expensive nature of the tests, extensive instrumentation has been applied to maximize the amount of information that can be obtained. The instrumentation has been chosen separately for each test considering the nature of the test and what has been learned from previous similar tests. The parameters that have been measured or otherwise determined in and after the tests include:

- impact velocity with laser sensors,
- impact forces with steel plate – load cell configuration,
- reinforcement strains with strain gauges and optic fibres,
- strains on the target surface with strain gauges,
- support forces with strain gauges or load cells,
- displacements with mechanical potentiometers or laser sensors,
- permanent deformations at specified point after the test,
- accelerations with accelerometers of different sensitivity,
- variation of pre-stressing forces on the stressing tendons with load cells and strain gauges,
- kinematics of the impacting projectiles with high speed video footage, especially the residual velocity of the projectile in case of perforation,
- penetration depth of the projectile,
- areas of spalled, scabbed and cracked concrete using photographs and drawing software,
- mass of detached concrete and
- mass of water that passes through the slab when perforated with a water filled projectile.

In addition to the forementioned parameters, some of the latest tested slabs were subjected to 3D scanning resulting information regarding the damage crater depth in 3D.

The Type and Development of The Projectiles

The projectile types used in the tests can be roughly divided into the following categories:

- hard projectiles,

- soft add semi-soft projectiles,
- water filled projectiles and
- winged projectiles.

There are different ways to define soft and hard impacts. Historically, a soft impact has been defined as such in which energy dissipation in the impact is complete and there is no rebound of the projectile. Another way to make this division is to study the deformation of the target. If the deformation is small, the problem can be solved by analysing the impacting projectile and the deforming target separately and the impact is considered as soft. The division method used in VTT tests is to compare deformability of the projectile to that of the target. If the projectile is much more deformable that the target, the projectile and the impact are classified as soft.

Most of the projectile types have evolved during the years. Modifications have been introduced when the behaviour of the earlier type has not anymore met the purpose it has been intended for. Versions of the winged, water filled and hard projectiles are shown in Figure 5.

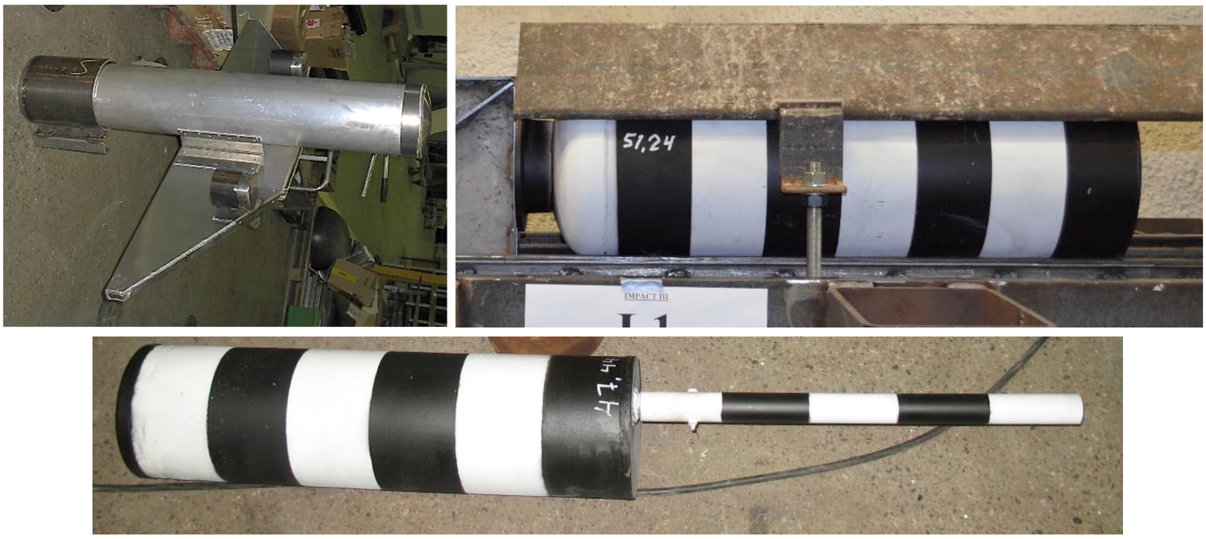

Figure 5. Top left: An aircraft model projectile used early in the test program. Top right: A water filled projectile maximizing the water mass. Bottom: A hard projectile.

Different versions of a soft projectile are shown in Figure 6. The studies were started by using a threaded steel pipe with a connected piston at the back, shot from inside of the acceleration tube. This threaded pipe was designed so that its force function resembled that of a real aircraft when scaled down to the same dimensions. Soon after started shooting of the projectiles from above the acceleration tube. The projectile material was changed to aluminum. A pair of steel claws were added beneath the projectile to help it stay on its path during acceleration. A heavy steel pipe was added at the rear of the projectile to add mass. The problem with the threaded pipe and aluminum projectiles was that the force that could be generated with them was inadequate to cause serious damage to the reinforced concrete slabs used as targets. In addition, aluminum projectiles did not behave predictably, one failing by crushing into crumbles, another by banana peeling and third by folding. To solve the force problem, the projectile material was changed to stainless steel. While having considerably larger crushing strength than an actual aircraft fuselage has, it behaves predictably can generate large enough force-time function to cause very high plastic elongations in the reinforcement of the target slabs.

Figure 6. Top left: A soft projectile-piston system made out of threaded pipe. Top right: An aluminium projectile with heavy steely back part. Bottom: A stainless steel projectile.

Force Plate Tests

Force plate tests have been carried out to validate the behaviour of a projectile type before applying it in an expensive rc target test and to obtain its force-time function so that it could be used as an input in simulations of the slab tests. This way modelling of the loading could be excluded as the reason for discrepancies between the simulated and the measured results. This held true especially in the first years of testing activities when inclusion of the projectile in the simulation was not feasible. Force plate tests have been carried out with soft, water filled and winged projectiles. In the test, a projectile is impacted against a thick steel plate with load cells attached behind it. Since the load cells are located behind the plate, the measured force includes also possible inertial forces of the plate. Examples of the tests results can be found for example in the work by Heckötter et al. (2022) and Vepsä et al. (2022B).

A special series of force plate tests was carried out with different types of water filled projectiles within SAFIR framework. The goal of the series was to quantify the spreading of the water from the tank in terms of spray front velocity in different directions at different times and the size and velocity distribution of the spray at specified distance from the impact point. These goals were obtained with aid of high and ultra-high speed video cameras and suitable analysis software. The results were used to validate CFD and fire simulation software. More information regarding the water spray tests can be found from the work by Silde et al. (2011) and Hostikka et al. (2015).

Hard Impact Punching Behavior Tests

The main goal of the punching tests has been validation of empirical and semi-empirical formulas that can be used to estimate punching resistance of rc slabs. In the recent years, reliable simulation of perforation of a rc slab by a hard projectile has become possible, even if not computationally very feasible. The test data can then be used also in validation of the simulation results.

Testing has been based on a base line specimen. This is a 250 mm thick slab having nominal concrete strength of C40/50 and longitudinal reinforcement of D10 rebars with spacing of 90 mm in both direction and both faces. Test parameters have then been added and changed test by test. Including all projects, the parameter variation has included

- impact velocity,
- slab thickness: 125+125 mm double wall (SAFIR) / 250 / 300 / 350 mm,
- longitudinal reinforcement: none (SAFIR) / D10 cc 90 / D10 cc 45 / 2D10cc90 / D16 cc90,
- shear reinforcement: none - D10 & D12 T-headed bars / D10 C-shaped stirrups,
- pre-stressing: none / bars only / ~5 MPa / ~10 MPa / ~10 MPa with grouted bars,
- steel liner at the rear surface,
- impact angle:60 / 70 / 90° ,
- maximum grain size: 8 / 32 mm (SAFIR) and
- concrete nominal strength: C40 / C70.

In addition to intentional change of concrete strength, unintentional change has been introduced by natural scatter in the realized strength. The impact velocity has been chosen so that it would result desired amount of damage in the test, whether this means initiation of scabbing at the rear surface, perforation of the slab or some other type of damage. The parameter values in the list complemented with text (SAFIR) have been studied within SAFIR-framework. In the Impact projects, the project participant with the main responsibility for the design of the test series was CNSC.

Addition of new or enhancement of the old elements to/in the base line slab increases its punching resistance. For example, in their study, Galan and Orbovic (2015) determined the combined effect of shear reinforcement, pre-stressing and a liner to increase the ballistic limit by 20 - 25 %. This would mean 44 - 56 % increase in the critical energy required for perforation. Similar studies regarding the effect of shear reinforcement has been carried out by Orbovic et al. (2015A, 2015B). The effect of slab thickness and shear reinforcement in thicker slabs are studied in Vepsä et al. (2022A). The results show that relatively heavy shear reinforcement increases the slabs punching capacity slightly with slab thickness of 250 mm and that the effect seems to increase when the slab thickness is increased. The inclined punching behavior tests have been summarized in the work by Calonius et al (2022).

Soft Impact Bending Behavior Tests

The main goal of the bending behaviour tests has been to validate the numerical tools, methods and models. Once validated, they can be used in analysis of a real scale aircraft impact with increased and quantified reliability. The bending behaviour tests have been carried out with 150 mm rc slabs. Including all projects, the parameter variation has included

- impact velocity,
- longitudinal reinforcement: D6 cc 50 / D8 cc 50 / D8 cc 65
- shear reinforcement: none / D6 mm closed stirrups / C-shaped stirrups with reduced amount
- slab size: 2100*2100 mm / 2300*2000 mm
- supporting: 1-way / 2-way
- impact angle: 70 / 80 / 90 ° and
- splicing of reinforcement at the rear surface: continuous / overlapping.

While the nominal concrete strength was kept the same, natural variation in the realized values added concrete strength related parameters as test variables. The main responsibility of the series design within Impact-projects was carried by IRSN. More information regarding the bending behaviour tests can be found in the work by Tarallo and Rambach (2013). The work by Vepsä et al. (2022B) discusses the inclined bending behavior tests.

Liquid Effect Impact Tests

Liquid effect impact tests were carried out with similar slabs that were used in the bending behavior tests. Bending was the main response mode of the targets in majority of the tests. However, some of the tests were designed so that the main response mode was punching failure. This was achieved by maximizing the mass of the water inside the projectile and by using high enough impact velocity. In addition to computation model validation, the goal of the series was to study the load magnification effect caused by the heavy mass density of the water compared to comparison tests carried out with hollow projectiles with the same mass and impact velocity. Main responsibility of the series design was carried by IRSN in the first two Impact-projects and by GRS in Impact III project. More information regarding the tests, how they relate to similar hollow projectile tests and how they can be numerically simulated can be found for example in the work by Tarallo and Rambach (2013), Heckötter and Sievers (2015) and Heckötter et al. (2022).

Target vibration impact tests

The goal of the target vibration impact tests was to study how the soft impact induced shock waves propagate from the impact point to the distal parts of the structure, how the impact makes the structure to vibrate and how these properties change in subsequent tests when the structure is already partially damaged. The tests commonly included modal testing and analysis made after each test. The main responsibility of the series design was carried by VTT but heavy contribution to the series was made also by ENSI with the aid of SPI. One test in the series was carried out with the IRIS 3 mock-up after the IRIS 3 test series was finished. More information regarding the target vibration tests can be found in the work by Vepsä et al. (2017) and Borgerhoff et al (2019). Description of IRIS 3 project can be found from the work by Hervé-Secourgeon et al. (2016).

Knife effect impact tests

The knife effect refers to a phenomenon where the wings of an aircraft cut through the target wall like a knife cuts bread. A winged projectile was designed for the purpose of these tests. Some of the designs also incorporated the motors (solid steel cylinders) as well as "fuel" tank integrated into the wings. Only a limited series of force plate tests and one 150 mm thick slab test was carried out with the winged projectiles. Some of these tests have been discussed in the work by Kuutti and Lastunen (2009).

Combined bending and punching behavior tests

In combined bending and punching tests, 250 mm thick rc slabs were subjected to impacts of a semi-soft projectiles. The goal of the 13 test series was to study how different test parameters contributed to the balance between bending and punching response of the target. All the tests were carried out within Impact projects where ENSI was the project participant with the main responsibility for the design of the test series. The balance between the bending and punching behaviour was varied by changing the projectile properties like the mass and the ratio between the crushing strength and the mass flow as well as by changing the type and amount of shear reinforcement. The test series and its results have been discussed for example in the work by Borgerhoff et al. (2013, 2015).

Material tests

The impact tests have been accompanied by selection of material tests that have been carried out for selected projectile materials, target reinforcement rebars and the batch(es) of concrete used to cast the targets. All the material tests have been quasi-static with some limited study regarding the effect of loading speed within quasi-static regime. The projectile and reinforcement material has been subjected to tensile tests giving us the stress-strain curves, yield strength, ultimate strength, ultimate elongation and total elongation under maximum load. All these values are engineering ones. With development and employment of digital image correlation technique, true strain and stress values have been obtained for few material batches.

Concrete was initially subjected to the basic material tests of unconfined compression strength, splitting tensile strength and Young's modulus. With increasing awareness of concrete's material properties' importance in the results, especially the punching resistance, more versatile testing schedule was undertaken. These tests include

- unconfined compression strength tests with strain gauge instrumentation, both force and displacement driven, resulting stress-strain diagrams,
- secant modulus tests resulting also Poisson's ratio,
- cyclic secant modulus tests resulting secant modulus as a function of axial strain in both loading and unloading,
- 3-point bending tests resulting fracture energy and tensile strength and
- triaxial compression strength tests with 50% and 100% confinement pressures resulting stress-strain diagrams.

FUTURE

Currently the tests that can be carried out at VTT are limited to square slabs with span width of 2.0 metres and 3D structures and impact energies of around 700 kJ. In future, VTT offers opportunity to test targets with larger dimensions using heavier projectiles and higher impact velocities. This is enabled by a completely new apparatus shown in Figure 7. The apparatus will be ready and in operation in late 2022. The new test bed will enable usage of projectiles with a diameter up to 500 mm and square targets with a span width of 3.5 m enabling study of the scaling effect as the same tests can be carried out in scales of 1 and 1.75. One of the main differences to the old apparatus is that the projectiles will be shot from inside the tube.

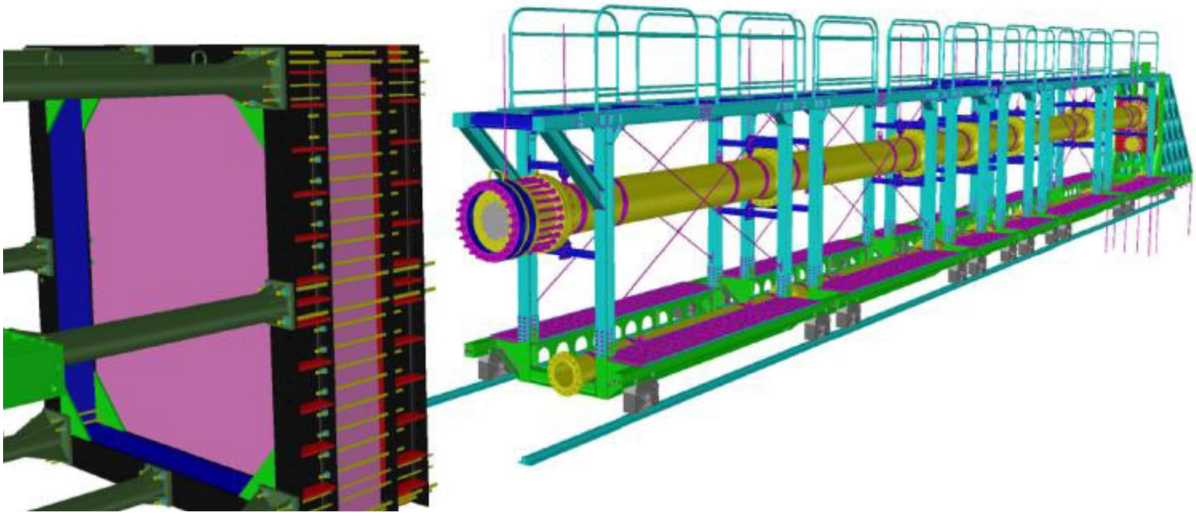

Figure 7. Second generation impact testing apparatus.

REFERENCES

Borgerhoff, M., Schneeberger, C., Riesner, F., Stangenberg, F., Zinn, R. (2019). "Impact Induced Vibrations Of Reinforced Concrete Structures Determined By Linear And Nonlinear Analyses Of

Tests Performed Within IMPACT III Project," *Transactions of SMiRT-25*, Charlotte, US, August, 2019.

Borgerhoff, M., Rodríguez, J., Schneeberger, C., Stangenberg, F., Zinnm R. (2015). "Knowledge Gained from Further IMPACT III Project Tests of Reinforced Concrete Slabs Showing Combined Bending and Punching Behaviour," *Transactions of SMiRT-23*, Manchester, UK, August, 2015.

Borgerhoff, M., Zinn, R., Schneeberger, C. (2013). "Conclusions from combined bending and punching tests for aircraft impact design," *Transactions of SMiRT-22*, San Francisco, US, August, 2013.

Calonius, K., Saarenheimo, A., Fedoroff, A., Vepsä., A. (2022). "Punching failure of reinforced concrete slabs subjected to hard missile impact, Part II: recent tests and analyses on inclined impact," *Transactions of SMiRT-26*, Berlin, Germany, July 10-15, 2022.

Galan, M. and Orbovic, N. (2015). "Quantification of perforation resistance of prestressed walls with transverse reinforcement and liner under hard missile impact based on test results", *Transactions of SMiRT-23*, Manchester, UK, August 10-14, 2015, Paper ID 554. 10 p.

Heckötter, C., Vepsä, A., Sievers, J. (2022). "Test program and numerical studies on reinforced concrete slabs impacted by liquid-filled missiles," *Transactions of SMiRT-26*, Berlin, Germany, July 10-15, 2022.

Heckötter, C. and Sievers, J. (2015). "Impact of different sized deformable projectiles with and without liquid filling," 23*rd International Conference on Structural Mechanics in Reactor Technology (SMiRT-23)*, Division IV, Manchester, United Kingdom.

Hervé-Secourgeon, G., Galan, M., Darraba, A. (2016). "IRIS Phase 3 - Description of IRIS Phase 3 Project", EDF, Revision C. DOI:10.13140/RG.2.2.33147.41760

Hostikka, S., Silde, A., Sikanen, T., Vepsä, A., Paajanen, A., Honkanen, M. (2015). "Experimental characterisation of sprays resulting from impacts of liquid-containing projectiles," *Nuclear Engineering and Design*, Volume 295, 15 December 2015, pp 388-402. https://doi.org/10.1016/j.nucengdes.2015.09.008

Kuutti, J. and Lastunen, A. (2009). "Studies of Medium Scale Non-axisymmetric Missile Impacts", *Transactions of SMiRT-20*, Espoo, Finland, August 9-14, 2009.

OECD NEA. (2012) "Improving robustness of assessment methodologies for structures impacted by missiles (IRIS_2010). Final report," 2012, OECD/NEA website.

Orbovic, N., Sagals, G. and Blahoianu, A. (2015A). "Influence of transverse reinforcement on penetration resistance of reinforced concrete slabs under hard missile impacts," *Nuclear Engineering and Design*. 295, pp 716-729. http://dx.doi.org/10.1016/j.nucengdes.2015.06.007

Orbovic, N., Galan, M. and Blahoianu, A. (2015B). "Hard impact tests in order to assess the effect of pre-stressing on perforation capacity of concrete slabs," *Transactions of SMIRT-23*, Manchester, UK, August 10-14, 2015, Paper ID 241, 8 p.

Silde, A., Kankkunen, J., Juntunen, J. (2009). "Study of Liquid Dispersal from a Missile Impacting a Wall," 20*th International Conference on Structural Mechanics in Reactor Technology (SMiRT-20)*, Division 5, Espoo, Finland.

Tarallo, F., Rambach, J.-M. (2013). "Some Lessons Learned from Tests of VTT IMPACT Program, Phases I and II," In Transactions of SMiRT 22, San Francisco, USA, 2013.

Vepsä, A., Heckötter, C, Darraba, A., Fedoroff, A., Sawada, S., Schneeberger, C., Tarallo, C. (2022A) "Punching Failure of Reinforced Concrete Slabs Subjected to Hard Missile Impact, Part I: Recent Tests on Influence of Slab Thickness and Shear Reinforcement," *Transactions of SMiRT-26*, Berlin, Germany, July 10-15, 2022.

Vepsä, A., Heckötter, C, Darraba, A., Fedoroff, A., Sawada, S., Schneeberger, C., Tarallo, C. (2022B) "Bending damage of reinforced concrete slabs subjected to soft missile impact, Part I: Recent tests on influence of inclined impact," *Transactions of SMiRT-26*, Berlin, Germany, July 10-15, 2022.

Vepsä, A., Calonius, C., Saarenheimo, A., Aatola, S., Halonen, M. (2017). "Soft impact testing of a wall-floor-wall reinforced concrete structure," *Nuclear Engineerign and Design*, Vol. 311, Jan. 2017, pp 86-103. https://doi.org/10.1016/j.nucengdes.2016.10.052