IRIS_2010 - PART II: EXPERIMENTAL DATA

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ABSTRACT

The benchmark IRIS_2010 is an exercise in OECD/NEA/CSNI framework. This exercise concentrates on improving robustness assessment methodologies for structures impacted by missiles. This paper is the 2nd of a series of 5 companion papers (references [1] through [4]) that present different aspects of the exercise. It concentrates on experimental testing and results of the tests as they were measured.

The experimental tests included into the exercise consisted of two tests for bending, three for punching and one for combined punching and bending behavior of reinforced concrete walls under impact loading. The test for combined behavior was performed by Hochtief AG in Meppen, Germany in the 1980's, while all the other tests were carried out by VTT Technical research centre of Finland in Espoo, Finland, during the spring of 2010.

In the tests performed at VTT, the walls were simply supported at all of their four sides with the span width being 2 m. All the walls were reinforced with bending reinforcement in both horizontal and vertical directions with the horizontal rebars being nearer to the surface of the wall. The walls used in tests for bending behavior were 150 mm thick. All these "bending" walls included also shear reinforcement. The bending walls (B1 & B2) were tested by impacting a deformable stainless steel missile against them. The mass of the missiles was 50.5 kg and the target value for the impact velocity was 110 m/s. The walls used in tests for punching behavior (P1-P3) were 250 mm thick and they did not include shear reinforcement. These "punching" walls were tested by impacting a non-deformable missile with mass of roughly 47.5 kg against them with the target impact velocity being 135 m/s.

Main instrumentation in the tests carried out by VTT consisted of strain gauges placed on the reinforcement rebars as well as on the front surface of the wall, strain gauges on the supports of the mounting frame of the wall to compute the support forces, five sensors for measurement of displacements and high shutter speed video cameras to record the impact. All in all, the tests succeeded quite well with the realized input values being quite close to their target values. It also seems that the tests are fairly repeatable which was one of the objectives set for the tests. The results act as reliable reference data against which predicted results can be compared.

In the Meppen test, tagged here as MII-4, a 700 mm thick reinforced concrete wall was impacted with a deformable missile with mass of 1016 kg and with the realized impact velocity being 247.7 m/s. Span width of the wall was 5.4 meters and it was both simply supported at each side and additionally tied to the supporting system with tie-rods. Support forces generated during the impact were measured with multiple load cells and strain gauges on the tie-rods. Displacements and accelerations were measured at the back surface of the wall and strains were measured from the reinforcement at multiple locations.

INTRODUCTION

Two distinct structural behaviors of concrete walls under impact of a colliding object have been studied experimentally in multinational projects called IMPACT I and II. Implementation of the test series has been carried out by VTT. The studied behaviors are bending and punching behavior of the wall. When studying punching behavior, a reinforced concrete wall is subjected to an impact of a non-deformable missile. In the punching behavior, the response of the wall to the impact is rather local: the missile tries to penetrate through the wall with only little or none global response of the wall. When studying bending behavior, a reinforced concrete wall is subjected to impact of a deformable missile. In this bending behavior, the response of the wall to the impact is global. Motivation for the study arises from the terrorist attacks against the World Trade Centre towers in 11.9.2001.

The benchmark IRIS_2010 concentrates on similar issues than what has been studied within IMPACT I & II. Twenty organisations from all over the world are taking part in this exercise. Reliable and relevant experimentally obtained test data, acting as reference results, is necessity for this benchmark to be successful. It was decided that five impact tests should be performed on concrete walls for the purposes of the benchmark. Since VTT has all the necessary equipment and knowhow to perform the tests, and it has shown capability of performing this type of tests during the IMPACT projects, it was natural choice for the provider of the tests.

Two of the tests to be performed concentrated on bending response of the wall while the three remaining tests concentrated on punching behavior of the wall. One additional test, combining both punching and bending behaviour and carried out in Meppen, Germany in the 1980's by Hochtief AG, was also included in the IRIS_2010 reference data. The objective of this test series was to provide necessary experimental data for the IRIS_2010 benchmark. This paper describes the bending behavior tests B1 and B2, the punching behavior tests P1 - P3 and the combined punching and bending behaviour test MII-4.

TESTING APPARATUS USED IN THE TESTS B1-B2 AND P1-P3

A sketch of the testing apparatus is shown on the left in Figure 1. The basic idea is to use air pressure in acceleration of the missile to its target speed. Pressure is gradually increased in the pressure accumulator tube until it reaches a predefined test-specific value. The pressure accumulator tube is separated from an acceleration tube on the right by a flange with a set of plastic membranes taped on both sides of the flange. When the predetermined value of pressure is achieved, the plastic membranes gets punctured and released pressurized air pushes the piston, which is located inside the acceleration tube. The missile rests on rails which are located on top of the acceleration tube. In an acceleration phase, the missile is pushed by a fin of the piston. While the missile continues its flight and ultimately hits the target, the piston is stopped by a piston catcher before it hits the target. The wall to be tested is mounted on a steel frame which rests on wooden planks as shown on the right in Figure 1. The frame is supported in horizontal direction by four supports called back pipes.

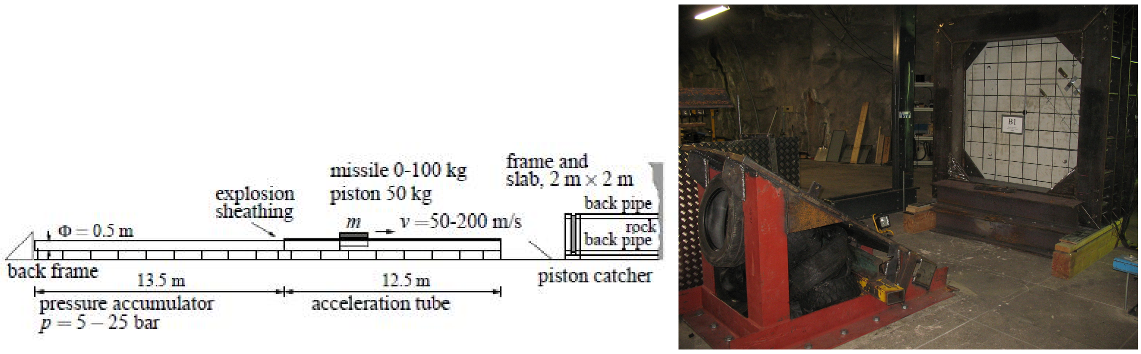


Figure 1. Left: Test apparatus. Right: The wall in the test B1 as mounted on the frame.

INPUT DATA FOR THE TESTS

The missile types used in the tests are shown in Figure 2. On top of the figure is the missile used in the test MII4. On the bottom row are the missiles used in the tests B1 and B2 (on the left) and in the tests P1-P3 (on the right).

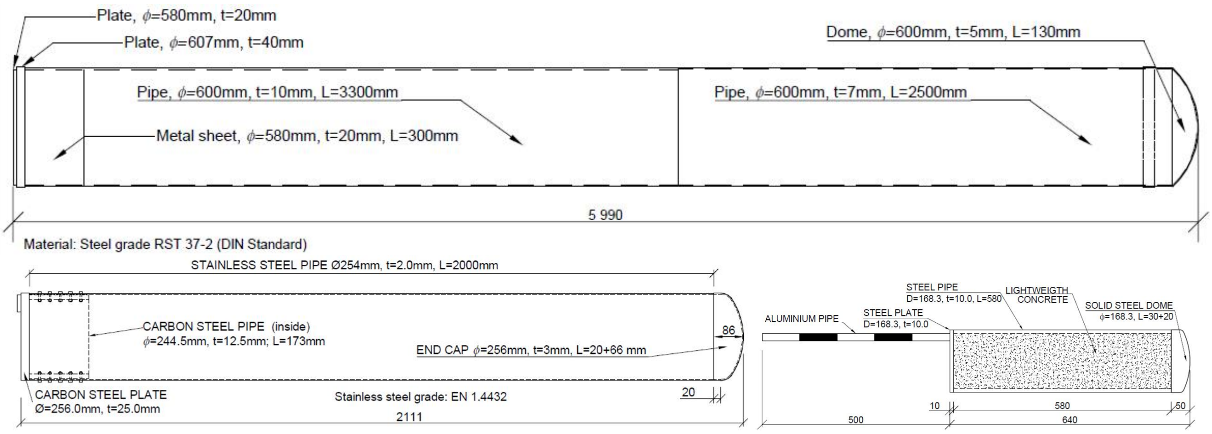


Figure 2. Top: A deformable missile used in the test MII-4. Bottom left: A deformable missile type used in the tests B1 and B2. Bottom right: A non-deformable missile type used in the tests P1-P3.

In the tests carried out at VTT, the impact velocity of the missile was measured using laser beams running orthogonally across the flying path of the missile near the target. The impacts were documented visually using three high shutter speed video cameras with two of them taking footage from the front side of the wall in an oblique angle and the third from the backside of the wall also in an oblique angle. Footage taken by these high shutter speed cameras was also used as a mean of determination of the residual velocity in the punching behavior tests. Data measured during the tests was recorded on two computers with sampling frequency of 102.4 kHz. The data from the high shutter speed video cameras was recorder on their own memory cards.

Realization data of the tests is collected in Table 1. This data includes missile type, realized impact velocity with an estimate for the limit of error in the parenthesis and hit point of the missile as well as mass of the missile in each test. The hit point is expressed as a distance from the target point in both horizontal and vertical directions. Table 2 shows geometric properties of the tested walls together with the reinforcement information. Material properties of the used batches of concrete and reinforcement steel are collected in Table 3. Concrete for the tests carried out at VTT was tested for unconfined compression strength, f_c, splitting tensile strength, f_{ctk}, and Young's modulus, *E*. Reinforcement steel for the tests carried out at VTT was tested for tensile strength. Obtained numerical values of the yield strength, f_y, ultimate strength, f_u, and total elongation, ε_u, are shown in the table. All the aforementioned properties were tested in static tests with 3 specimens and the values shown are the averages of the individual results. Only engineering stresses and strains were measured. Only compression strength of concrete and the type of reinforcement steel was known for the test MII-4. Early stages of the stress-strain curves obtained from the tensile tests for reinforcement used in the tests B1, B2 and P1-P3 are shown in Figure 3. The graph (a) is for the tests B1 and B2 and the graph (b) is for the tests P1-P3.

Table 1. Realized input values for the tests.

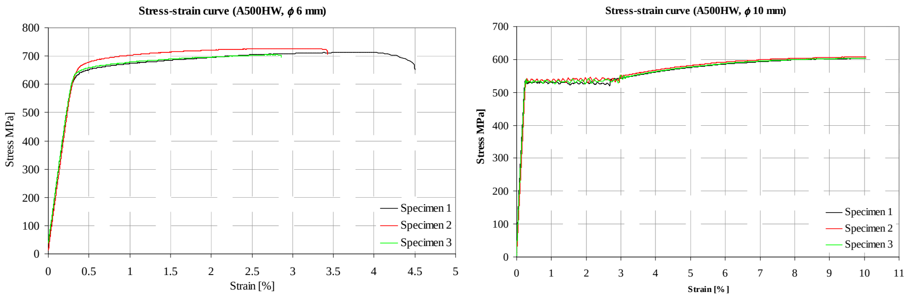
Test	Missile type	Impact velocity [m/s] (±0.5m/s)	Hit point [mm] + direction	Missile mass [kg]
P1	Non-deformable	135.9	5 ←, 8 ↑	47.38
P2		134.9	5 ←, 8 ↑	47.46
P3		136.5	20 →, 30 ↑	47.32
B1	Deformable	110.2	20 ←, 9 ↑	50.50
B2		111.6	3 →, 17 ↑	50.48
MII-4		247.7	N/A	1016

Table 2. Geometrical properties of the tested walls and information concerning reinforcement and concrete cover.

Test	Thick-ness	Side width/Support width	Reinforcement		Concrete cover
			Bending	Shear	
	t	w/w$_s$	Diameter, D / Reinf. ratio, A_s	Diameter, D_τ / Reinf. ratio, $A_{s\tau}$	
	[mm]	[mm]	[mm] / [cm^2/m]	[mm] / [cm^2/m^2]	[mm]
P1-P3	250	2100/2000	ϕ10 c/c 90 / 8.7	None	20
B1&B2	150	2082/2000	ϕ6 c/c 55 / 5.1	ϕ6 / 44.1	15
MII-4	700	6000/5400 (Vertical) 6500/5400 (Horizontal)	ϕ28 / 53.6 (Rear) ϕ20 / 27.3 (Front)	ϕ20 / 50.2	20

Table 3. Material properties for concrete and reinforcement rebars used in the tests.

Test	Concrete			Steel		
	f_c	f_{ctk}	E	f_y	f_u	ε_u
	[MPa]	[MPa]	[GPa]	[MPa]	[MPa]	[%]
P1	67.1	4.04	29.429	540.0	605.3	18.67
P2	64.7	3.34	27.535			
P3	64.9					
B1	63.9	3.71	26.915	661.7	715.0	10.13
B2	66.5					
MII-4	37.3	N/A	N/A	N/A, Steel type BSt 420/500 RK		



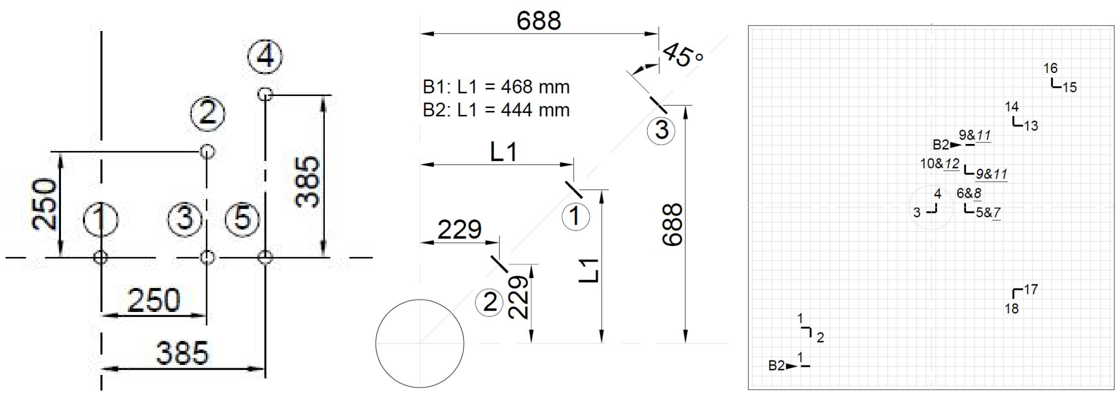
(a) Tests B1&B2 (b) Tests P1-P3

Figure 3. Early stages of the stress – stain curves for the reinforcement rebars used in the tests B1&B2 and P1-P3.

INSTRUMENTATION AND THE RESULTS

The bending behavior tests B1&B2

Figure 4 shows the locations of the measurement devices used in the bending behavior tests B1 and B2. The frame (a) represents the displacement sensors, the frame (b) the strain gauges on the front surface of the wall and the frame (c) the strain gauges on the rebars. In the frame (c), the gauges written in italic and underlined letters are located on the rebars near the front surface of the wall. The viewpoint is from the front in all of the three frames in the figure.



(a) Displacement sensors (b) Strain gauges on the front surface (c) Strain gauges on the rebars

Figure 4. Placement of the measurement devices in the tests B1 and B2.

Figure 5 shows high shutter speed video footage from the bending behavior test B1. The frames are taken from the front side of the wall roughly 5, 10, 15 and 20 ms after beginning of the impact. The impact lasted approximately 18 ms in both of the tests B1 and B2.

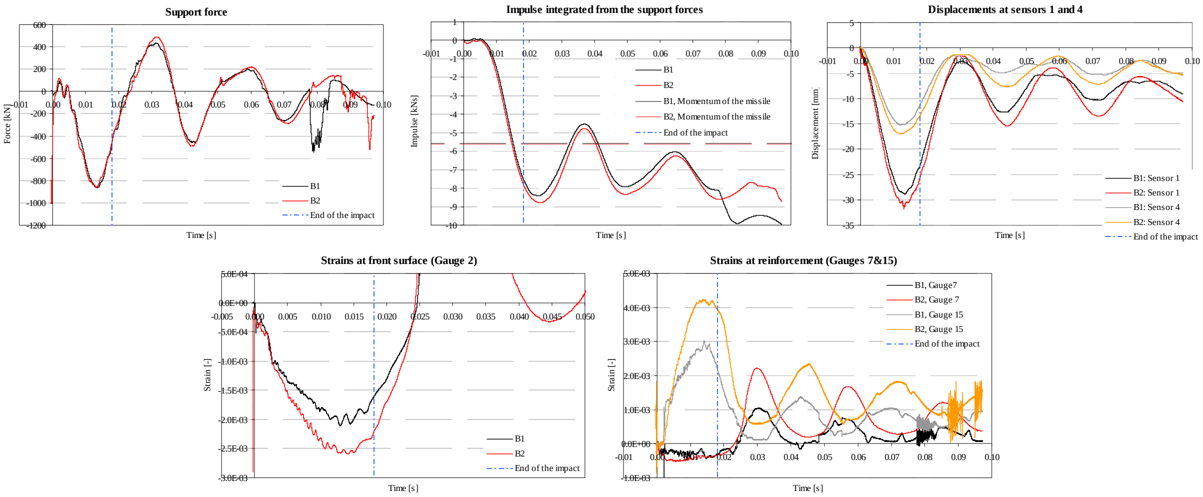
(a) at t≈5ms (b) at t≈10ms (c) at t≈15ms (d) at t≈20ms.

Figure 5. Snapshots of the impact at different moments in the bending behavior test B1.

Apart from some minor splitting which happened at the front end of the missile in the test B1, the missiles behave well with a clear folding pattern. In the test B1, the missile shortened 971 mm if the folded part is taken into account and 1156 mm if it is neglected. The number of folds was 22. The corresponding values in the test B2 were 991 and 1181 mm with 25 folds.

Figure 6 shows selected results measured during the tests B1 and B2 as a function of time. The curves in black and grey were measured in the test B1 and the ones in red and orange in the test B2. The blue vertical dot-and-dash line marks the estimated end of the impact. The graph (a) shows the combined support force measured from the backpipes during the tests. The measurement system has been calibrated with static compression tests but naturally there are some uncertainties associated with the measured values. The measured support forces include additionally some measurement noise induced remnant forces which are not there in reality. The graph (b) shows the impulse integrated from the support force with respect to time. The horizontal dashed lines in this graph show the momentum of the missile at the moment of the impact. As a result of the remnant forces in the measurement, the impulse increases with time without limits. The graph (c) shows the displacements measured during the tests with sensors 1 and 4. An estimate for the limit of error for displacements is ±2 % and due to inaccuracies in calibration of the sensors. The graph (d) shows the strain measured with gauge number 2 at the front surface of the wall. The gauges on the front surface work properly only in compression due to cracking of concrete in tension. Therefore the results shown in the frame after ~25 ms are not relevant. The final graph (e) shows the strains measured at the reinforcement rebars with gauges number 7 and 15. The gauge number 7 was located on a rebar near the front surface of the wall while the gauge number 15 was located on a rebar near the back surface of the wall. This explains why the strains measured with the gauge number 15 have maximum values at the same time than the strains measured with the gauge number 7 have their minimum values and vice versa. The error in measurement of strain is theoretically ±1 % and due to accuracy of the value for the gauge factor.

(a) Support forces (b) Impulse integrated from the support forces (c) Displacements at sensors 1 & 4



(d) Strains on the front surface (e) Strains on the reinforcement

Figure 6. Selected results from the bending tests B1 and B2.

The combined punching and bending behaviour test MII-4

The test MII-4 was carried out under supervision of GRS in Meppen, Germany by Hochtief AG in the framework of German reactor safety research program between 1974-1982. This framework was funded by the German Federal ministry of Research and Technology. The test is discussed in the report by Jonas et al. [5].

The tested wall was instrumented with 55 strain gauges glued on the bending as well as shear reinforcement. Displacements and accelerations were measured at the back surface of the wall with 8 sensors each. Support reaction forces were measured with 8 force transducers. Figure 7 shows locations for the instrumentation as well as supports used in the test. Selected results from this test are shown in Figure 8. The graph (a) shows the reaction forces K1, K5-K8 and the graph (b) the displacements W1, W3, W5 and W7 on the right half of the wall. The graph (c) shows the strains measured with gauges 9-10, 23-24, 50 and 52 on the reinforcement.

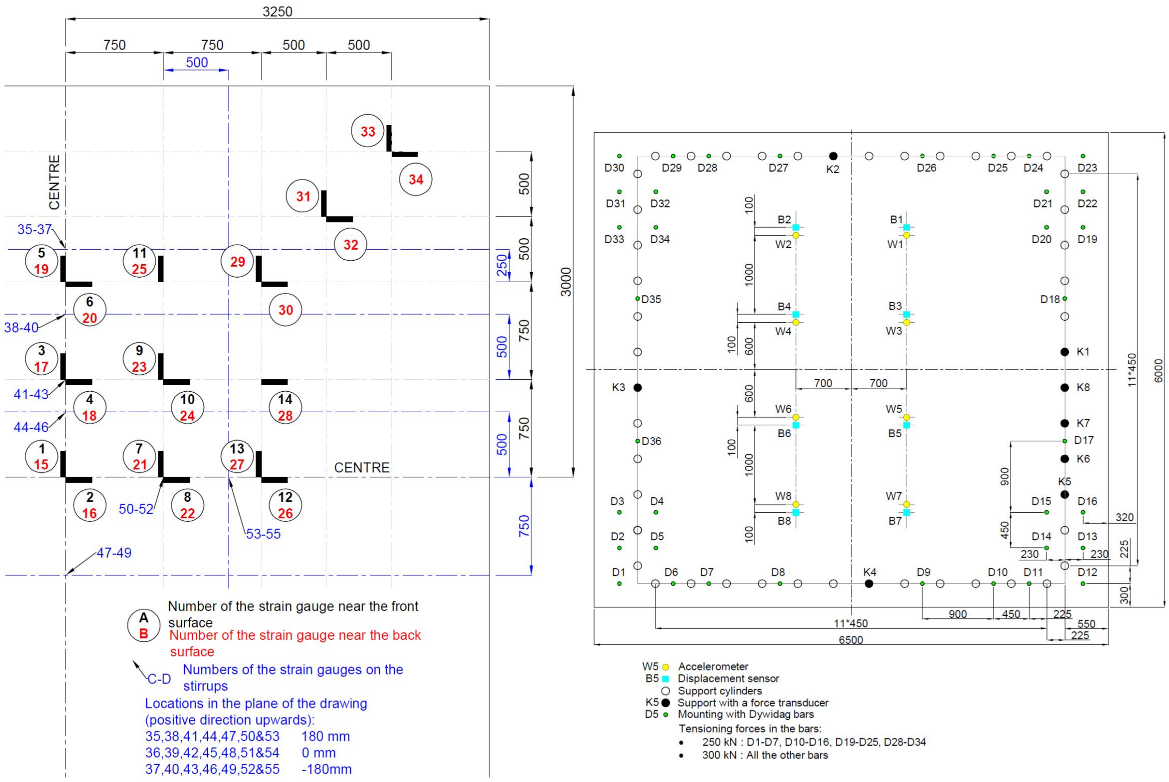
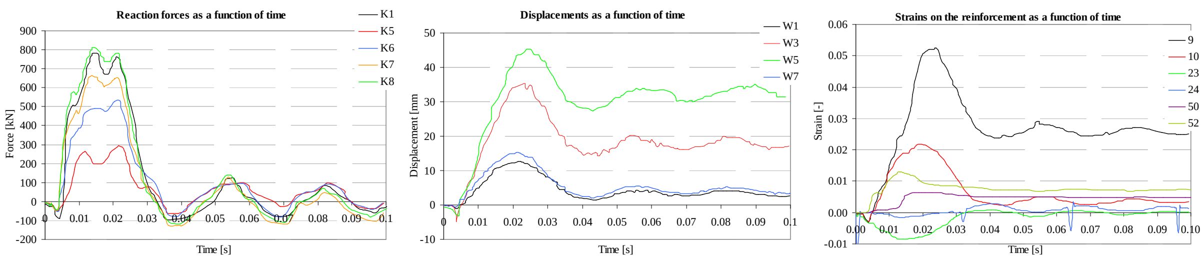


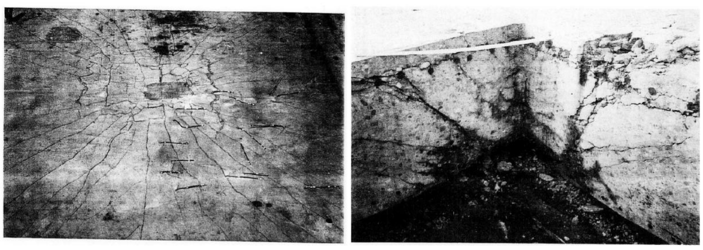
Figure 7. Locations of the measurement devices in the test MII-4. Left: Strain gauges on the reinforcement rebars. Right: Supports, force transducers, accelerometers, displacement sensors and mountings with Dywidag bars.



(a) Reaction forces K1, K5-K8 (b) Displacements W1, W3, W5 & W7 (c) Strains on the reinforcement

Figure 8. Selected results from the test MII-4.

Close-up photographs of the wall after the test are shown in Figure 9. The photograph (a) shows the crack distribution at the back surface while the photograph (b) shows the crack distribution across the wall near the centre after the wall has been sawn. The backside of the wall is pointing upwards in the photograph (b).



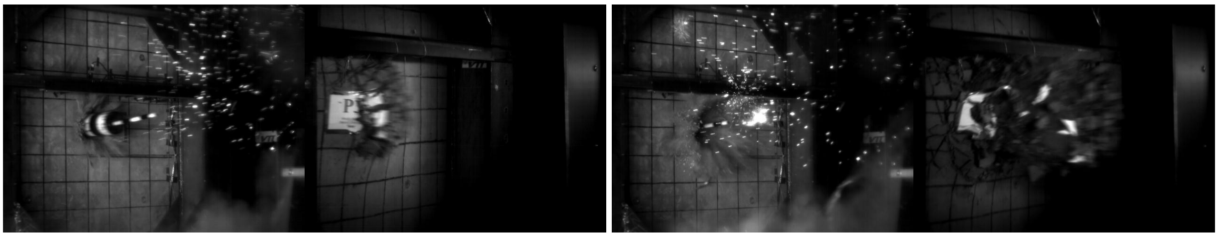
(a) Back surface (b) Cross section near the centre of the wall

Figure 9. Crack distributions of the wall after the test MII-4.

The punching behavior tests P1-P3

Figure 10 shows high shutter speed video footage from the punching behavior test P3. The first two frames on the left are taken roughly 5 ms and the last two frames on the right roughly 15 ms after beginning of the impact. The first and the third frame are taken from the front side of the wall while the second and the forth frame are taken from the backside of the wall at the corresponding moments. As can be seen, the missile perforates the wall and causes a layer of concrete to come loose at the back surface of the wall (scabbing). This perforation happened in each punching behavior test.

Front side Backside Front side Backside



(a) t≈5ms (b) t≈15ms

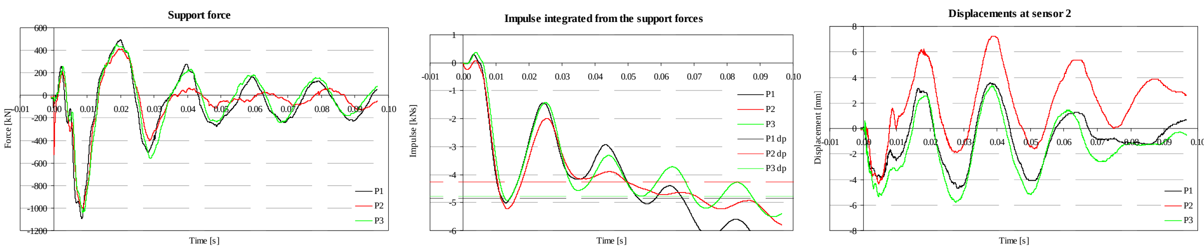
Figure 10. Snapshots of the impact in the punching behavior test P3.

The main results of the tests P1-P3 are collected in Table 4. These results include residual velocity of the missile after it had perforated the wall, the number of broken vertical (↕) and horizontal (↔) rebars on the front- and backside of the wall and areas where spalling and scabbing of concrete occurred at the front and back surface of the walls. Estimated limits of error for residual velocity and damaged areas are given in the parentheses.

Table 4. The main results of the punching behavior tests.

Test	**Residual velocity [m/s] (~±2m/s)**	**Number of broken rebars**		**Damaged areas [m^2]**	
		Front side	**Backside**	**Spalling (~±0.01 m^2)**	**Scabbing (~±0.02 m^2)**
P1	34	1 ↕ + 1 ↔	2 ↕ + 2 ↔	0.107	1.01
P2	45	2 ↕ + 1 ↔	2 ↕ + 2 ↔	0.103	1.00
P3	36	2 ↕ + 1 ↔	2 ↕ + 2 ↔	0.095	1.12

The graph (a) in Figure 11 shows the support force measured from the backpipes during the tests. The graph (b) shows the impulse integrated from the support force with respect to time. The horizontal dashed lines in the graph show the level of momentum that the missile looses during the impact. The graph (c) shows the displacements measured at the front surface above the centre point of the wall. The same limits of error apply as for the bending behaviour tests B1 and B2.



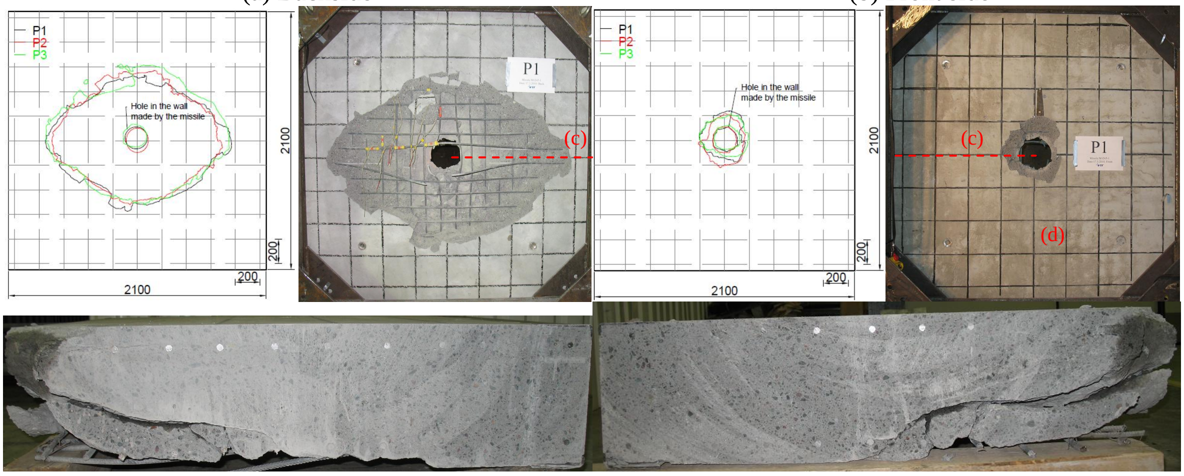
(a) Reaction forces (b) Impulse integrated from the support forces (c) Displacements

Figure 11. Selected results from the punching behaviour tests.

Figure 12 shows how large were the damaged areas of walls in the punching tests. The drawings show the scabbed area at the backside of the wall (a) and the spalling area on the front side of the wall (b). The circular shapes near the centre represent the holes made in the walls by the missile. Photographs in the figure show damage of the wall in the test P1. The frames on the upper row represent the backside (a), viewed form the back, and the front side

(b) of the wall after the test. The grid on the surface of the wall is drawn with 200mm*200mm spacing. The frames on the bottom row represent the horizontal (c) and the vertical (d) cross-section of a cut lower left quadrant of the wall. The front side is up in both of these two bottom row frames. The cut quadrant is marked with dashed red lines in the photographs representing the back and the front side.

(a) Backside (b) Front side



(c) Horizontal cut (d) Vertical cut

Figure 12. Schematic drawings of the damage of the wall with scabbing and spalling areas and photographs showing the damage in the test P1.

CONCLUSION

Five impact tests were carried out at VTT in which a missile was impacted against a reinforced concrete wall. Two of these tests were so called bending behavior tests in which the used missile was deformable and the response of the wall global (bending). The three other tests were so called punching behavior tests in which the used missile was non-deformable and the response of the wall merely local (perforation). Both the bending tests as well as the punching tests were meant to be identical with each other. The tests succeeded well: both the realized input values as well as the measured results show only small variance between the tests of the same type. The only exception was the strains measured at the reinforcement for which higher discrepancies between the similar tests were found. These five tests were funded by VTT, IRSN and CNSC and they were carried out for the purposes of the IRIS_2010 benchmarking exercise in the OECD/NEA/CSNI framework. This exercise includes additionally one combined punching and bending behavior impact test carried out in Meppen, Germany in the 1980's with a deformable missile. The data obtained from these six tests is used as reference data in the benchmark against which predictions given by numerical models and analytical or experimental formulas are compared.

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