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COMBINED BENDING AND PUNCHING DAMAGE OF REINFORCED CONCRETE SLABS UNDER IMPACT LOADING: TESTS ON INFLUENCE OF SCALE EFFECT

Alexis Fedoroff[1], Anthony Darraba[2], Sara Ghadimi Khasraghy[3], Christian Heckötter[4], Genadijs Sagals[5], Shohei Sawada[6], Guilherme Soares[1], Francois Tarallo[7], Ari Vepsä[1]

[1] Senior Scientist, VTT Technical Research Centre of Finland, Espoo, Finland (alexis.fedoroff@vtt.fi)
[2] Expert Engineer, Électricité de France EDF, Lyon, France
[3] Civil Engineering Specialist, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland
[4] Technical Expert, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Cologne, Germany
[5] Technical Specialist, Canadian Nuclear Safety Commission (CNSC), Mississauga, Canada
[6] Group Leader, Kajima Corporation, Tokyo, Japan
[7] Civil Engineer - Senior Expert, Institut de Radioprotection et de Sûreté Nucléaire IRSN, Fontenay-aux-Roses, France

ABSTRACT

The purpose of this study is to illustrate the sensitivity of a set of combined bending and punching impact tests on reinforced concrete slabs with respect to geometric scaling laws. As a part of the fourth phase of a multinational research program IMPACT (IMPACT IV – NEREID project), a pair of impact tests are carried out that aim at studying the scalability of the reinforced concrete slabs subjected to impact of semi-rigid projectiles. The test results exposed here do not show any obvious signs of scale sensitivity. However, further experiments may be required to confirm the scalability of the impact tests.

INTRODUCTION

Protection of nuclear power plant structures against external impact threats, such as airplane crashes, is necessary to ensure proper operation and/or safe shutdown. Significant efforts have been made to the study of various failure mechanisms within the frame of the international IMPACT program. Since the tests within the previous phases of the IMPACT program (IMPACT I – III projects) have been conducted on smaller specimens, it is important to understand the role of the test setup scale and how it affects the measured mechanical response. For example, in the fracture mechanics it has been discussed that a smaller specimen can carry a greater relative strength, Bazant (1992). In the domain of impact testing on concrete structures, Sage and Pfeiffer (1979) as well as Rüdiger and Riech (1983) conducted smaller scale replica test of larger scale Mappen tests and noticed minor effects due to geometric scaling. Likewise, Sugano et al. (1993) and Hering et al. (2022) investigated the effect of geometric scaling at three different scales. Overall, as a general outcome these studies did not show strong scale dependency. However, in order to validate the working hypothesis of scale insensitivity more tests may need to be conducted. Within the fourth phase of the IMPACT project (IMPACT IV – NEREID), investigation of the scale effect is one of the top priorities of the project. To carry out impact tests at multiple scales, VTT has invested in an updated impact test facility in 2021-2022. Currently the upgraded test facility is in use and the present work relates the outcome of the first test set with the new test device that focuses on scale sensitivity issues.

SCALING LAWS

Testing at small scale is indispensable because full scale testing is usually prohibitively costly. Impact tests are conducted on reduced scale models in order to get the response of a geometrically similar full-scale prototype. The process is referred to as replica scaling, and it is subject to certain governing principles. These principles predict how the different parameters of the test (such as specimen length, mass, impact velocity) should be scaled and how response measurements (such as displacement, strain, impact time, frequency) should be scaled. In a uniform isotropic geometric scaling, each spatial dimension is scaled with the same scaling factor, λ. Derived quantities are therefore scaled by powers of the scaling factor. Table 1 shows the scaling laws for some of the most common parameters of the impact tests. Notice, although a material parameter is invariable to scaling, that strain rate sensitivity of a material parameter is dependent on the scaling factor in a very non-linear manner, Jones (1984). Another important issue is that in a given test setup it is often very difficult to construct the test in such a way that both the impacting projectile and the target slab are rigorously scaled. For example, due to restriction of reinforcement steel diameter to certain values (6mm, 8mm, 10mm, 12mm, 16mm, …) it is possible to scale precisely only the overall cross-sectional area per unit of length of the reinforcement by adjusting the c/c distance between the reinforcement. Likewise, if the projectile is manufactured using some structural hollow core pipe, only the dimensions that are available from the manufacturer can be used. Therefore, it is inevitable that the parameters of the test setup are a compromise between the ideal set of parameter values and the adapted set of parameter values due to manufacturing restrictions.

Table 1: Scaling of most common parameters.

Test parameters	**Scaled by**	**Measurements**	**Scaled by**
Spatial dimensions [m]	λ^1	Displacement [m]	λ^1
Volume [m^3]	λ^3	Strain [mm/mm]	λ^0
Cross sectional area [m^2]	λ^2	Stress [N/m^2]	λ^0
Cross sectional area [m^2/m]	λ^1	Force [N]	λ^2
Cross sectional area [m^2/m^2]	λ^0	Time [s]	λ^1
Mass [kg]	λ^3	Frequency [1/s]	λ^{-1}
Density [kg/m^3]	λ^0	Fracture stress [N/m^2]	$\lambda^{-1/2}$
Impact velocity [m/s]	λ^0	Bouncing velocity [m/s]	λ^0

TEST SETUP DESCRIPTION

The test setup consists in a pressurized air shooting device, which shoots the projectile at a desired impact velocity against a target. The target is either a thick steel plate with force transducers to record the force-time curve or a square shaped reinforced concrete slab that is held in place in a steel frame, which provides pinned boundary conditions for the slab. The flying projectile crosses laser beams, which cuts the electric circuit. Estimation of that time event enables the calculation of the impact velocity. High speed cameras provide visual information, which can be post processed in various ways, notably using Digital Image Correlation (DIC) to measure kinematic data. The test slab is instrumented with strain gauges glued on the reinforcement steel and displacement sensors attached at the back surface of the target slab. Figure 1. Provides a schematic view of the test setup.

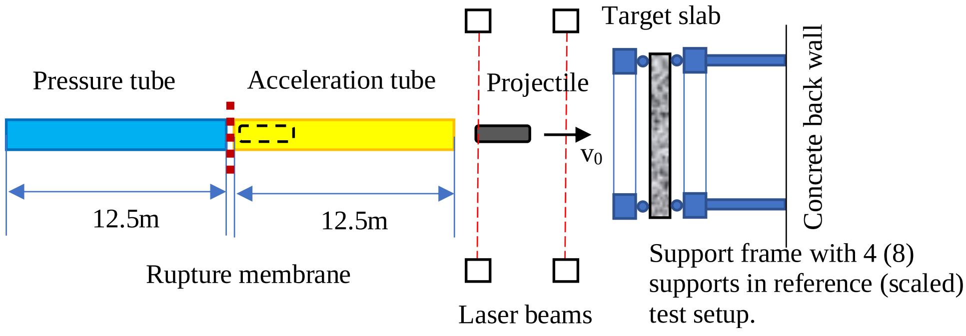

Figure 1. Schematic view of the test setup

Modularity of the testing device enables currently the testing at a reference small scale and at a larger scale with geometric scale factor 1.75. Figures 2a and 2b show the test setup for both scales. The test setup allows the testing of various types of impact: deformable projectiles are used to investigate the bending response of the reinforced concrete target slab under a mass flow dominated loading, whereas semi-rigid projectiles are used to investigate the combined punching and bending behaviour under a loading with important crushing force. Rigid projectiles are used to investigate the local punching resistance of the target slab. The tests described here are designed to promote the combined punching and bending behaviour of the slabs.

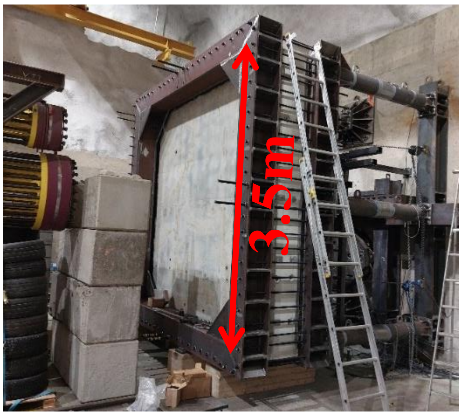

Figure 2a. Picture of scaled test (λ = 1.75)

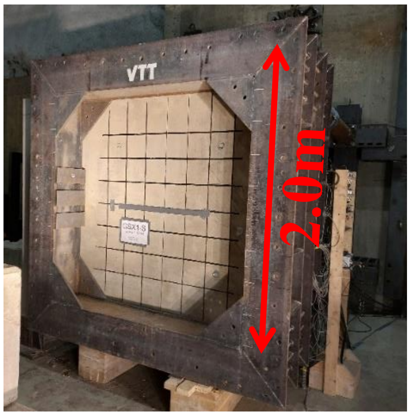

Figure 2b. Picture of reference test (λ = 1.00)

TEST PARAMETERS

To study the scale sensitivity of the response of a concrete slab under a combined punching and bending failure, one has to conduct a set of one reference test and one scaled test[1]. In the test planning phase of the IMPACT IV – NEREID project, it was assumed that tests from previous test phases would serve as reference tests. However, due to the difficulty to maintain the same concrete parameters, it is necessary to replicate the reference test so that the target slab is cast with the same concrete batch. Furthermore, for practical reasons it is necessary to adjust some of the geometric scaling requirements. Therefore, the tests presented here is a standalone test, which makes no reference to any previous test campaigns. Table 2. shows the test parameters. The reinforcement steel spacing has been chosen in such a way that the shear reinforcement cross-sectional area A_{sv} is scaled properly. Hence the bending reinforcement is Ø10 c/c 90mm in both directions and on both surfaces, and the shear reinforcement is Ø6 c/c 180mm in the horizontal direction and 2Ø6 c/c 180mm in the vertical direction. Projectile outer diameter and thickness is determined by the stock availability. Notice, that the most important deviations from the geometric scale factor concerns the outer diameter of the projectile (the scaled test projectile is slightly larger than the reference counterpart) and the shear and bending reinforcement diameter (the scaled reinforcement diameter is relatively smaller that the reference counterpart). However, the cross-sectional area of the bending reinforcement is relatively larger than the reference counterpart. Figure 3 and Figure 4 show the drawings of the projectile and target slab, respectively.

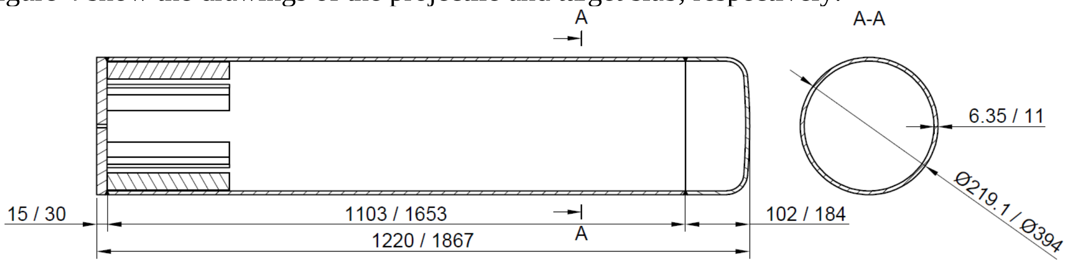

Figure 3. Drawing of projectile (not in scale)

[1] In IMPACT IV – NEREID nomenclature the reference test is denoted GSX1-S and the scaled test GSX1-L. Originally the IMPACT III phase test X3 was intended to be the reference test, but due to the addressed problems, the reference test was redesigned as GSX1-S.

Table 2: Test parameters.

Test parameters	Reference test (GSX1-S)	Scaled test (GSX1-L)	Scaling factor	Relative difference
Slab length, L_{slab} / span , L_{span} [mm]	2088 / 2000	3590 / 3500	1.75	-2 %
Slab thickness, t_{slab} [mm]	250	437.5	1.75	0 %
Slab concrete cover [mm]	20	35	1.75	0 %
Slab mass [ton]	2.71	13.9	1.72[3]	-4 %
Bending reinforcement, $Ø_b$ [mm]	10	16	1.60	-9 %
Bending reinforcement, A_{sb} [mm^2/m]	873	1676	1.92	10 %
Shear reinforcement, $Ø_v$ [mm]	6	8	1.33	-24 %
Shear reinforcement, A_{sv} [mm^2/m^2]	1745	1745	1.00	0 %
Projectile outer diameter, D_o [mm]	219.1	394	1.80	3 %
Projectile wall thickness, t [mm]	6.35	11.00	1.73	-1 %
Projectile mass [kg]	50	268	1.75[3]	0 %

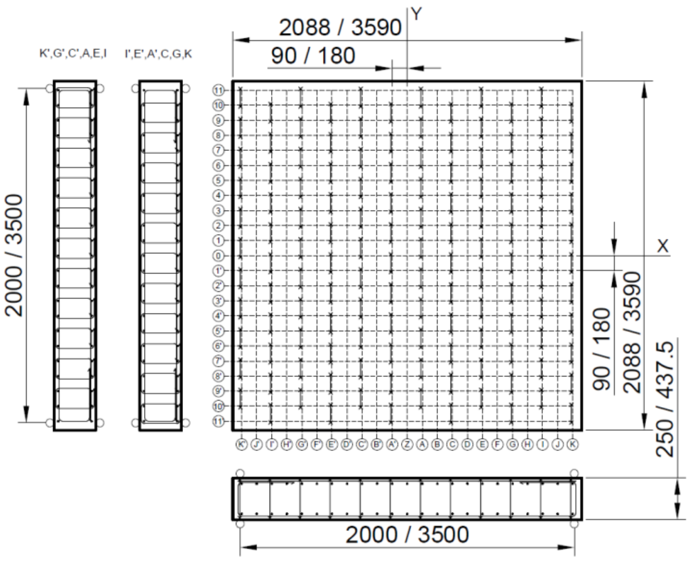

Figure 4. Drawing of target slab (not in scale)

MEASUREMENT METHODS

Projectile Velocity Measurements

Two pair of lasers (emitter and receiver units) are mounted on the path of the projectile as well as a cutwire installed on the slab surface. Whenever the laser line is crossed by the projectile or the current in the cutwire is cut due to impact, a change in voltage signal is observed and the corresponding time stamp is recorded. Knowing the distances of the lasers from the slab surface, one can compute the impact velocity form the difference quotient of distance difference with respect to time difference. High speed video footage can be used manually (counting frames) or with the help of computer algorithms to evaluate both the impact velocity and the bouncing velocity. In particular, the use of Digital Image Correlation (DIC) enables accurate measuring of displacements on the surface of the projectile prior, during, and after the impact, if its surface is visible. High-speed imaging was used to monitor the side of the projectile during using a Phantom Miro LC320S camera at acquisition rates up to 10 KHz. A custom calibration plate with known features and fiducials was designed for the spatial calibration of the system using a pinhole camera model. The projectile was painted with 10 cm black and white stripes for straightforward scaling and velocity measuring from imaging. Further spray-painted dots with different sizes were added to generate a random pattern, which could be used for automatic tracking of these features with DIC. Monitoring of how subsets of projectile surface moved between each image, full-field measurements of displacement were obtained from which velocity were also calculated. This approach enables accurate measurement of incoming speed, deceleration of projectile, and bounce back speed. The deceleration of the projectile can be estimated from fitting a polynomial to the displacement data, from which the second derivative can then be used to calculate the impact force as a function of time. This has been a versatile approach that has effectively worked for projectile of different sizes and tests with and without concrete targets. Figure 5. depicts an example image of calibration image and of a random pattern on projectile as well as the full-field displacement curve.

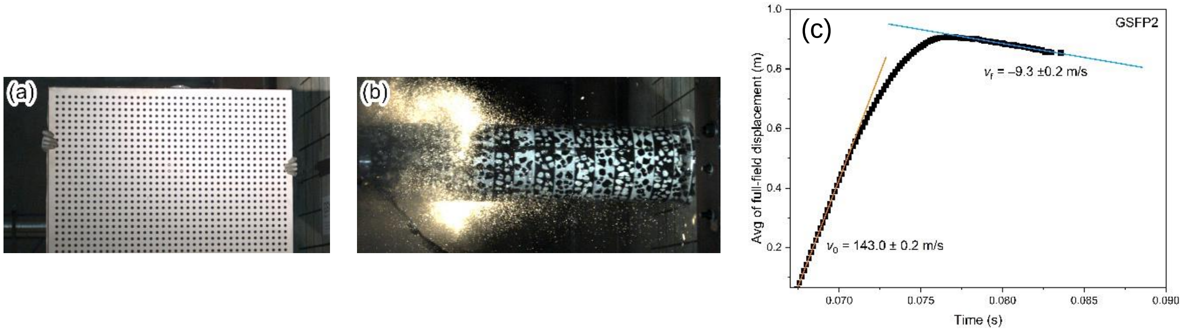

Figure 5. (a) Calibration plate used for calibrating pinhole camera model, (b) painted stripes and random pattern on surface of projectile used for carrying out DIC and measuring full-field displacements and (c) full-field displacement with linear fits for impact and bouncing velocities.

Strain Measurement of Reinforcement

Kyowa 5mm long strain gauge (KFEL-5-120-C1-11L1M2R) are glued to the reinforcement. The initial resistance of 120 Ohm of the strain gauge is affected by the strain state of the gauge, which in turn affects the off-balance state of the Wheatstone bridge. From the ratio of the bridge output and input voltages, one can deduce the strain value. A total of 8 strain gauges on bending reinforcement and 5 strain gauges on shear reinforcement were instrumented in the test. Figure 6 shows some selected results.

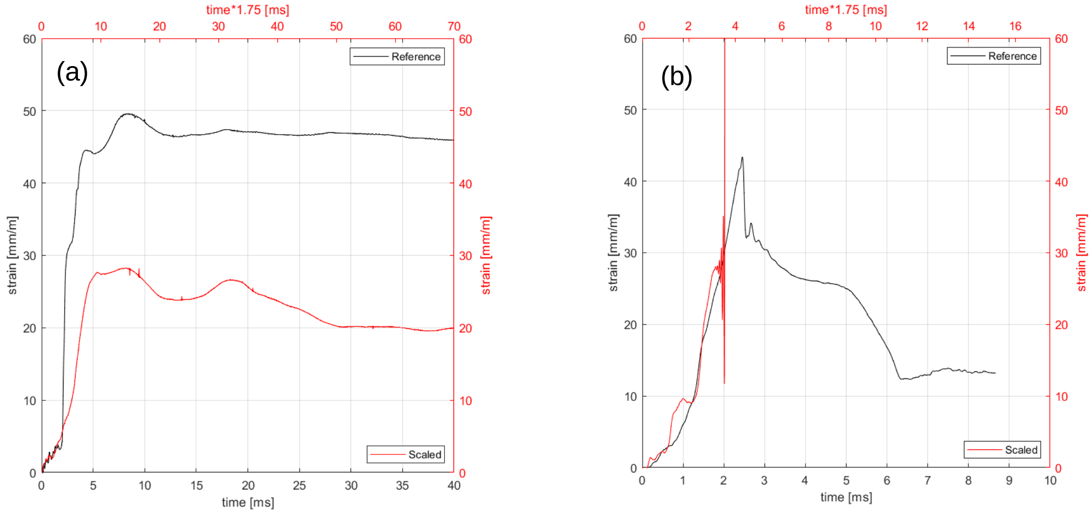

Figure 6. Comparison of strain measurements on (a) bending reinforcement in centre of slab and (b) shear reinforcement inside shear cone.

Displacement Measurement of Concrete Slab

Displacement measurement is done with 100mm potentiometer displacement sensors. The output voltage (sensor fully retracted: 0V, sensor fully extended: 5V) is directly converted into millimetres by applying a coefficient of 20 mm / V. A total of 7 displacement sensors were instrumented in the test, but due to massive scabbing at the back surface, most sensors failed to give meaningful data. Figure 7 shows some selected results.

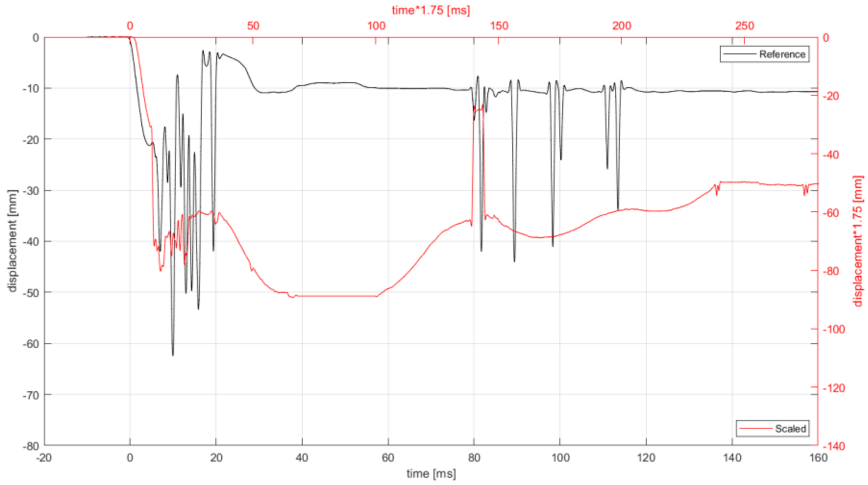

Figure 7. Comparison of displacement measurement at 950mm distance from slab centre.

Force Measurement

Force measurements of the projectile impacting a rigid orthogonal surface are carried out with 8 units of Kyowa BL200-TE and 6 units of Kyowa BL20012. The force transducers work on the same principle as the strain gauges (from the ratio of the bridge output and input voltages, one can deduce the strain and force values). The sum of forces transducer measurements and the corresponding impulse is shown in Figure 8. The mass of the rigid steel plate is 700 kg, and the rigidity of the force transducers can be considered as extremely high.

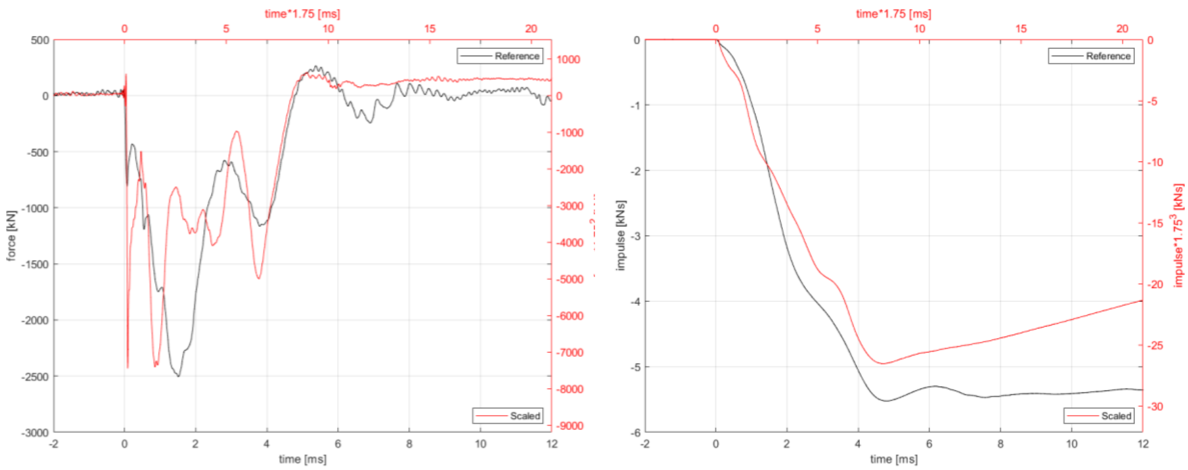

Figure 8. Comparison of (a) force measurements and (b) impulse measurements.

3D Scanning of Tested Target Slab and Projectile using Photogrammetry

Photogrammetry is a technique for measuring three-dimensional objects using the triangulation of identifiable features between photographs taken from different positions. In this work, it was carried out using RealityCapture software from Capturing Reality. Approximately 100 images with 4608 by 3456 pixels resolution and 24-bit depth were used for the reconstruction of the different projectiles and concrete targets. This method was successfully employed to obtain 3D models of projectiles and concrete targets of different sizes. Other useful outputs that were obtained from this method were cross-sections, orthographic projection, and depth map images. These were particularly useful for investigating the damage done by the projectile on both front and back faces of the concrete target, as well as the resulting folds that form in the front of the projectiles during the impact. Figure 9. shows a cross section of both a projectile and a concrete target obtained with photogrammetry. Figure 10. shows orthographic projections of target slab front and back surfaces as well as depth colormaps. All pictures shown in Figures 10 and 11 are from the scaled test (GSX1-L).

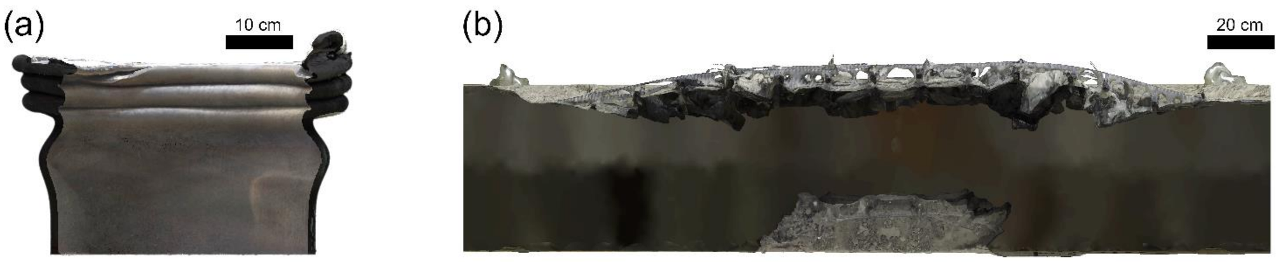

Figure 9. Orthographic projection of the central cross section of the (a) front of tested impact projectile and (b) concrete target. These are useful for investigating the folding mechanism in the projectile, and the damage caused by impact on the front and back of the concrete structure.

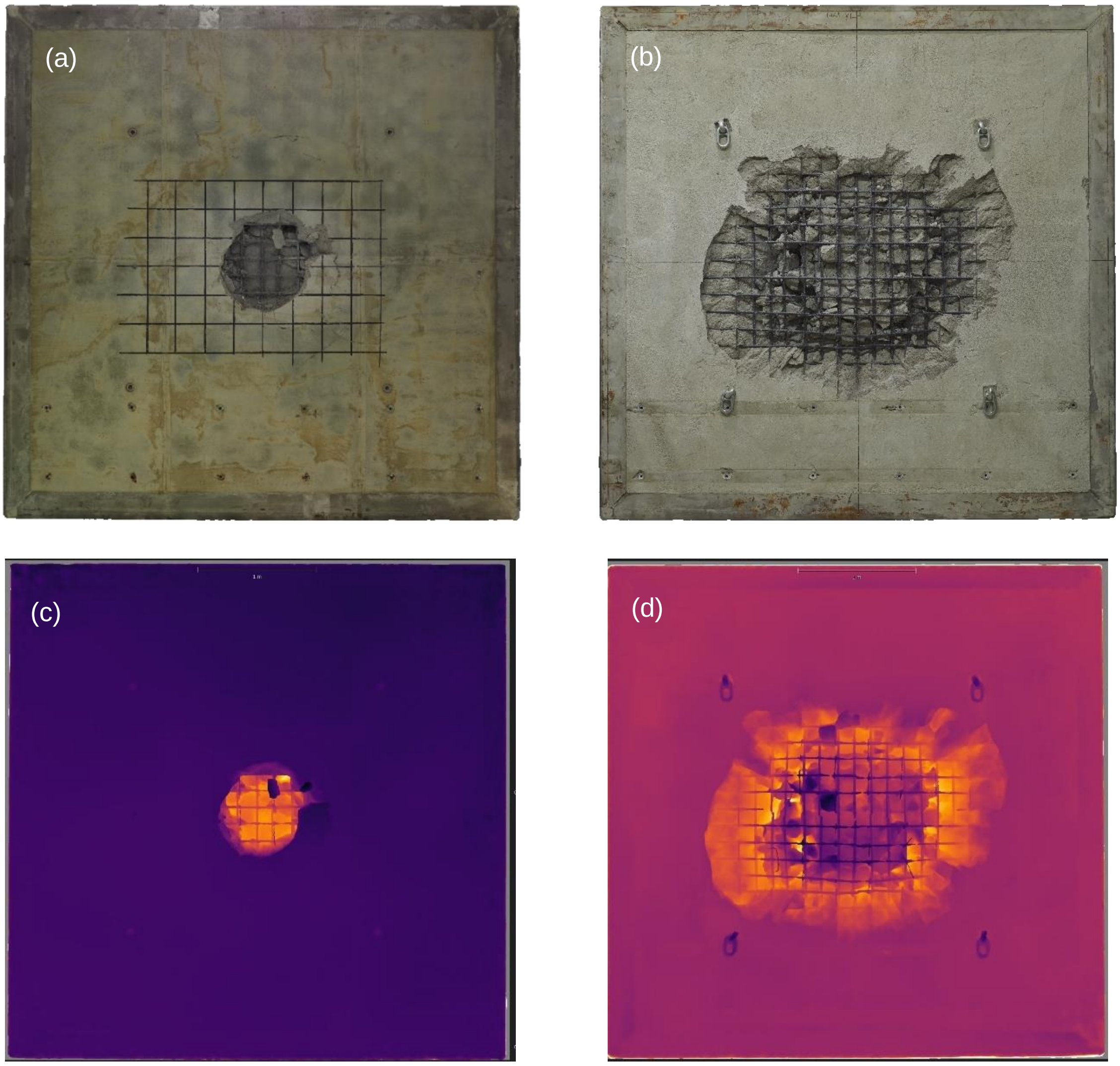

Figure 10. Orthographic projection of tested scaled slab (a) front surface, (b) back surface and depth color map projections of (c) front surface, (d) back surface.

RESULTS

The main results are summarized in Table 3. With R being the reference test result and S the scaled test result, the scaling factor is computed from $(S/R)^{1/p}$. The relative difference is computed form $(R - S/1.75^p)/R$. Material test results are shown in Table 4 and Table 5.

Table 3: Test measurements. No highlight: adherence to scaling laws. Red highlight: scaled result overestimating w/r to scaling laws. Blue highlight: scaled result underestimating w/r to scaling laws.

Test measurements	**Reference test (GSX1-S)**	**Scaled test (GSX1-L)**	**Scaling factor**	**Relative difference**
Impact velocity [m/s]	143	143	1.00	0%
Scabbed/loose concrete area [m2]	1.1	3.0	1.67	-9 %
Scabbed concrete mass [kg]	57.28	407.84	1.92	33 %
Tunnelling depth [mm]	110	120	1.09	-38 %
Broken bending reinforcement (front)	2 unit	0 unit	N/A	N/A
Broken bending reinforcement (back)	1 unit	0 unit	N/A	N/A
Broken shear reinforcement	80 %	88 %	N/A	N/A
Permanent strain (center, vert.) [mm/m]	46	17	0.36	-64 %
Permanent strain (center, hor.) [mm/m]	38	19	0.51	-49 %
Maximum strain (center, vert.) [mm/m]	50	28	0.57	-43 %
Maximum strain (center, hor.) [mm/m]	40	24	0.59	-41 %
Time at maximum (center, vert.) [ms]	8.4	14.4	1.71	-2 %
Time at maximum (center, hor.) [ms]	8.0	12.8	1.59	-9 %
Maximum force (fore plate test) [kN]	2507	7442	1.72	-3 %
Time at maximum (fore plate test) [ms]	1.5	1.5	0.99	-43 %
Impulse (fore plate test) [kNs]	5.5	27	1.69	-10 %
Impact velocity (fore plate test) [m/s]	143	143	1.00	0%
Bouncing velocity (fore plate test) [m/s]	9	9	1.00	0%
Projectile momentum (fore plate test) [kNs]	6.7	36	1.75	0%
Impact duration (fore plate test) [ms]	4.8	8.2	1.73	-1 %

Table 4: Concrete material parameters summary table.

C40/50 (material tests at 140 days, reference impact test at 185 days, scaled impact test at 163 days)	**Mean value**	**Standard deviation**
Compressive strength (f_{cm}) (lateral pressure 0%)	63.3 MPa	3.8 MPa
Compressive strength (f_{cm}) (lateral pressure 50%)	126 MPa	5.0 MPa
Compressive strength (f_{cm}) (lateral pressure 100%)	176 MPa	8.4 MPa
Modulus of elasticity, stabilized (E_{cm})	33.9 Gpa	0.1 GPa
Poisson ratio, stabilized	0.20 -	0.005 -
Split tensile strength ($f_{ctm,sp}$)	4.94 MPa	0.4 MPa

Table 5: Steel material parameters summary table.

	Measured quantity	Mean value	Standard deviation
S355 steel (projectile material)	Upper yield strength ReH [MPa]	370	0.58
	Tensile strength Rm [MPa]	533	1.00
	Elongation A [%]	28	0.29
B500B reinforcement steel, Ø6	Proof strength Rp0.2 [MPa]	573	2.3
	Tensile strength Rm [MPa]	612	4.2
	Total elongation Agt [%]	2.7	0.3
B500B reinforcement steel, Ø8	Proof strength Rp0.2 [MPa]	530	9.0
	Tensile strength Rm [MPa]	664	28.4
	Total elongation Agt [%]	8.2	1.0
B500B reinforcement steel, Ø10	Proof strength Rp0.2 [MPa]	515	2.0
	Tensile strength Rm [MPa]	600	4.9
	Total elongation Agt [%]	11.0	0.5
B500B reinforcement steel, Ø16	Proof strength Rp0.2 [MPa]	538	0.6
	Tensile strength Rm [MPa]	658	1.0
	Total elongation Agt [%]	8.5	0.5

DISCUSSION AND CONCLUSIONS

The impact test set presented in this study is a first-of-a-kind experiment carried out in VTT. It is clear, that from the manufacturing point of view the scaling of an impact test is not trivial, because many structural components used in the test, such as the reinforcement steel and the projectile, can be scaled only approximatively. Therefore, during the test design certain parameters are inevitably prioritized over other parameters. Since the expected failure mode is a combined bending and punching one, it is natural to choose the cross-sectional area of shear reinforcement per unit of area as the parameter, which is imperative to scale properly. It follows, that for some parameters (such as the cross-sectional area of bending reinforcement per unit of length) the scaling factor is overestimated, while for some other parameters (such as the reinforcement diameter) the scaling factor is underestimated. Since the observed failure mode is a complex one, it is impossible to tell, a priori, which test parameter the scaling laws are more sensitive to. One important test parameter is the aggregate size distribution in the concrete mix. It is tempting to opt for scaling of the maximum aggregate size. However, since it is imperative to have identical mechanical behaviour of concrete, the only way this can be practically achieved is by using the same concrete batch for both the reference test and the scaled test. Therefore, scaling of the maximum aggregate size is not possible due to practical considerations.

It has been observed in many previous works that the fracture behaviour of concrete in quasi-static tests is scale sensitive, the larger specimen being relatively less resistant to fracture than the smaller specimen. However, to the knowledge of the authors, such scale sensitivity has not yet been demonstrated in the domain of impact testing discussed in the literature. Most scale sensitivity studies on impact tests tend to be non-conclusive or the results show no scale sensitivity (i.e., adherence to the scaling laws). The test results of the present study show, indeed, some deviation from the scaling laws, but it can be argued that the deviations is an outcome of the deviation of the test parameters from proper scaling. The following details on scaling sensitivity are, nevertheless, worth mentioning:

- The overall damage state (punching dominated failure mode with important tunnelling, heavy scabbing and fragmented punching cone) in both test is comparable (scalable). The membrane effect of the bending reinforcement has stopped projectile perforation in both tests.
- The damage state of shear reinforcement is comparable in both tests. Within the shear cone 80%-90% of the shear reinforcement can be considered as broken.
- The damage state of the bending reinforcement is heavier in the reference test than in the scaled test, which can be observed in the amount of broken reinforcement as well as the strain levels. It can be argued that this is a consequence of the 10% overestimate of the cross-sectional area of bending reinforcement per unit of length for the scaled test.
- The force-time load function of the projectile obeys the scaling laws. This can be observed in the results of the impact tests against a rigid steel plate instrumented with force transducers. Both the maximum force, impact duration as well as the impulse obey well to the scaling laws.

Due to heavy damage and punching dominated failure mode, most of the displacement and strain measurements failed to produce relevant information. For "small" geometric scale factors, potential deviations from the scaling laws can be observed only with high precision measurements, which in turn are possible only if the damage state is less severe. In this geometrically scaled impact test, it has also been observed that deviations from the proper scaling in test parameters induce deviations from scaling laws in the test results. On the other hand, a larger scale factor would enable easier interpretation of the test results with respect to scaling sensitivity. The test results exposed here do not show, in the opinion of the authors, any obvious signs of scale sensitivity. However, disproving the claim that impact tests are scale sensitive requires numerous tests, both for statistic interpretation and to apply test parameter variation. It also needs to be acknowledged that the mechanisms that may or may not lead to scale sensitivity under impact loads are not well understood. It therefore necessitates, in addition to regular impact tests, also dynamic testing on material level for the determination of dynamic factors for material properties, and dynamic testing on structural component level for the understanding the dynamics of concrete-steel bonding and the concrete confinement effect.

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