

IMPACT LOADED REINFORCED CONCRETE SLABS IN COMBINED PUNCHING AND BENDING DAMAGE SCENARIO: EXPERIMENTAL EVALUATION OF THE SIZE-EFFECT

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ABSTRACT

The purpose of this study is to find whether reinforced concrete slabs undergoing combined punching and bending damage when subjected to impact of deformable projectiles are sensitive to geometric scaling. As a part of the fourth phase of a multinational research program IMPACT IV – NEREID, a pair of impact tests is carried out at different scales. The test results indicate scale sensitivity for this type of test, meaning that the larger specimen is relatively weaker than the smaller specimen. However, in order to confirm the statistical significance of this result, additional tests with a similar setup are needed.

INTRODUCTION

The commercial airplane crash scenario as a beyond design basis requirement for newly built nuclear power plants is established, in most countries, as part of nuclear safety research since the attacks against the World Trade Centre and Pentagon building on September 11, 2001. Prior to that event engineers have studied the effect of accidental crashes on nuclear powerplant structures, though. The experimental impact test campaign conducted at the test site in Meppen during the 1970s and 1980s, Heine and Jonas (1980), Nachtsheim and Stangenberg (1983), opened the era of systematic experimental impact testing with downscaled models of real structures. In Meppen series II tests, the mass of the projectile varies between 940 kg and 1060 kg with impact velocities between 148 m/s to 258 m/s and target structure thickness between 500 mm to 900 mm. Further, the Phantom F4 crash test in 1988 at Sandia National Laboratories, Sugano et al. (1993), is an important milestone in full-scale experimental impact testing. The weight of the aircraft was 19 tons and impact velocity against a rigid target was 215 m/s. Between 2004 and 2018 the Technical Research Centre of Finland (VTT) conducted three phases of the international research project IMPACT, phases I to III, which included various experimental campaigns on downscaled test specimens. In these tests, the mass of the projectile varied between 46.9 kg and 58.6 kg, the impact velocity between 59 m/s and 167 m/s, and target structure thickness between 150 mm and 250 mm.

Size-effect concerning impact response of concrete structures has been studied in the past. For example, Sage and Pfeiffer (1979) as well as Rüdiger and Riech (1983) conducted smaller scale test of Meppen tests and noticed minor effects due to geometric scaling. Likewise, Bracklow et al. (2022) investigated the effect of geometric scaling at three different scales with propulsion assisted drop-load tests at TU Dresden. Overall, as a general outcome these studies did not show strong scale dependency. From

2019 to 2025 VTT conducted the test campaign IMPACT IV – NEREID, where one of the goals is to evaluate the importance of size-effect in impact testing. Impact tests were conducted on reinforced concrete slabs with two different scales: in reference scale small test projectiles of 50 kg were accelerated against a 250 mm thick target slab (2 m × 2 m) while in the larger scale test 268 kg projectiles impacted a 438 mm thick slab (3.5 m × 3.5 m). The geometric scaling factor is thus 1.75. Both slabs were subjected to impact velocity of 143 m/s.

SIZE-EFFECT IN EXPERIMENTAL TESTING

Size-effect is present in a material test if the nominal stress at failure (force at failure divided by the ligament area) depends on the size of the structure. This observation is true in brittle and quasi-brittle materials (such as concrete), as detailed in Bazant (1992). In the literature, size-effect is explained either by statistics or by fracture mechanics. For large metal structures, size-effect is traditionally explained by weakest link statistics. Concrete structures, however, behave differently. Due to reinforcement as well as the existence of strain-softening in a large zone of microcracking ahead of the tip of a continuous crack, concrete structures do not fail at crack initiation. Hence, reinforced concrete structures with stress redistributions can be considered as a combination of structural elements with series and parallel couplings, and the weakest link theory does not apply. In concrete structures, size-effect can be better explained by the energetic (deterministic) size-effect based on fracture mechanics. According to the first law of thermodynamics, the accumulated potential energy release rate from the structure is equal to the energy dissipated by the fracture process (per unit crack band extension). Following Bazant (1984), one can derive a relation between the failure stress and the size factor, which on a logarithmic plot has an asymptote of slope $\frac{1}{2}$. Reinhardt (1981) also ends up with the same conclusion. Typically, the non-linear curve is fitted from experimental data points. The best results for curve fitting are obtained if there are enough data points for a wide range of scale factors. Size-effect in quasi-brittle materials under quasi-static loading has been studied extensively in the past, but extension of these studies to dynamic loading has also been studied. A study on uniaxial compression of concrete cylinders at quasi-static, 5 m/s and 7 m/s loading shows, that size-effect is visible from the test results for all loading rates, Elfahal, et al. (2005). As a matter of fact, size-effect is even more pronounced for dynamic loading rates. Indeed, it can be shown, Jones (1990), that the size-effect of material strain rate sensitivity is a non-linear function.

To conduct a geometric scale sensitivity test, the same test setup is replicated at different scales. It is important to notice, that in the experimental setup all geometric, kinematic and loading parameters should be scaled by the geometric scaling rules, while all material properties are kept unchanged. The scaling rules for most common parameters are listed in Table 1. Experiments are conducted on two different scales and the response (displacement, stress, strain, force, ...) is measured. The size-effect relation gives the measured response as a function of the scale parameter. It is convenient to normalize the measured quantity with respect to the measured quantity at reference scale. The normalized data points can then be plotted on logarithmic axes, and one can calculate a fitting function by minimizing the sum of residuals squared. It is important to notice, that the scaling laws are represented on a normalized logarithmic plot by straight lines through the origin. Hence, by observing the function fitted through the normalized data points relative to the scaling law lines, one can make conclusions about the nature of the observed size-effect.

Table 1: Scaling of most common parameters.

Test parameter	Scaled by	Measurement	Scaled by
Spatial dimensions	λ^1	Displacement	λ^1
Volume	λ^3	Strain	λ^0
Cross sectional area	λ^2	Stress	λ^0
Cross sectional area	λ^1	Force	λ^2
Cross sectional area	λ^0	Time	λ^1
Mass	λ^3	Frequency	λ^{-1}
Impact velocity	λ^0	Bouncing velocity	λ^0

Scaling of reinforced concrete slabs poses two practical problems: how to scale the reinforcement and how to scale the aggregates. Because reinforcement is an industrial product, it is available only in a finite range of dimensions. This constraint can be bypassed by scaling precisely the overall cross-sectional area per unit of length of the reinforcement (reinforcement ratio), which is done by adjusting the centre-to-centre distance between the bars. As far as concrete aggregates are concerned, according to the geometric scaling rules the material parameters for concrete should be identical at all scales. Hence, there are two options: either one considers the aggregate size as an integrant part of the concrete material property, and hence the aggregate size should remain invariant. Or, alternatively, one considers the aggregate size to be a geometric dimension and hence it should be scaled. If the concrete aggregates are scaled, one should make sure that the macroscopic properties (compressive strength, compressive stiffness, tensile strength, fracture energy, ...) of the concrete mix with different aggregate size should be identical. From a practical perspective this requirement of identical material parameters is very hard to achieve. The practical choice is to use the same concrete batch to cast the specimens at every scale to assure the same concrete properties.

In quasi-static tests the loading force is scaled, according to the geometric scaling rules, by the scale factor to the power of 2. On hydraulic test machines this constraint is easy to fulfil. However, in impact tests the loading is provided by a more or less deformable projectile, and the deformation of the projectile is also prone to size-effect. There are two mechanisms that explain the size-effect of the load function caused by a deforming projectile. First, as we previously mentioned, strain rate sensitivity of metal strength and ductility affects the sensitivity to geometric scale during plastic deformation of the projectile, which in turn affects the load function. Second, larger scale projectiles are more prone to fracture, which in turn also affects the load function, because the energy dissipated in plastic deformation is larger than the energy dissipated during fracture propagation. The size-effect in metal fracture is explained by the dependence of mode I fracture toughness on the specimen wall thickness. At smaller scale, plane stress state conditions hold in thin wall sections, which in turn results in higher values for fracture toughness. On the contrary, at larger scales, the plane strain conditions hold, which result in smaller values for fracture toughness. Hence, in the end, the size-effect observed in impact tests is always a balance between the scale sensitivity of the projectile and the scale sensitivity of the target structure.

The major difficulty in experimental observation of size-effect is to isolate the size-effect from stochastic variability in the test outcome. This leads to the following major observations: 1) Tests should be preferably performed in the same laboratory and roughly at the same time to avoid inconsistencies in the test setup. 2) The size range should be large in order to distinguish the size-effect.

TEST DESCRIPTION

The scale sensitivity tests focus on impacts with a semi-rigid projectile that promote a combined bending and punching failure mechanism of the target reinforced concrete slab. Two different scales are considered here. The scale factor for the small reference test is 1.00 and for the larger test is 1.75 (compared to the small test). The test setup consists of a pressurized air shooting device, which accelerates the projectile to a desired impact velocity against a target. The target is a square reinforced concrete slab that is held in place in a steel frame, which provides pinned boundary conditions for the slab. The test setup in both scales is shown in Figure 1.

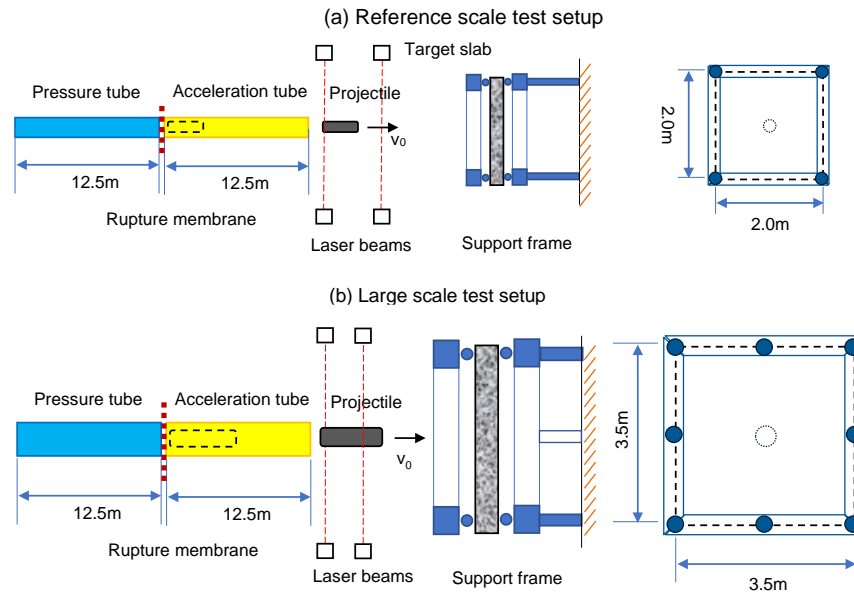


Figure 1. Schematic view of (a) reference scale test setup and (b) large scale test setup.

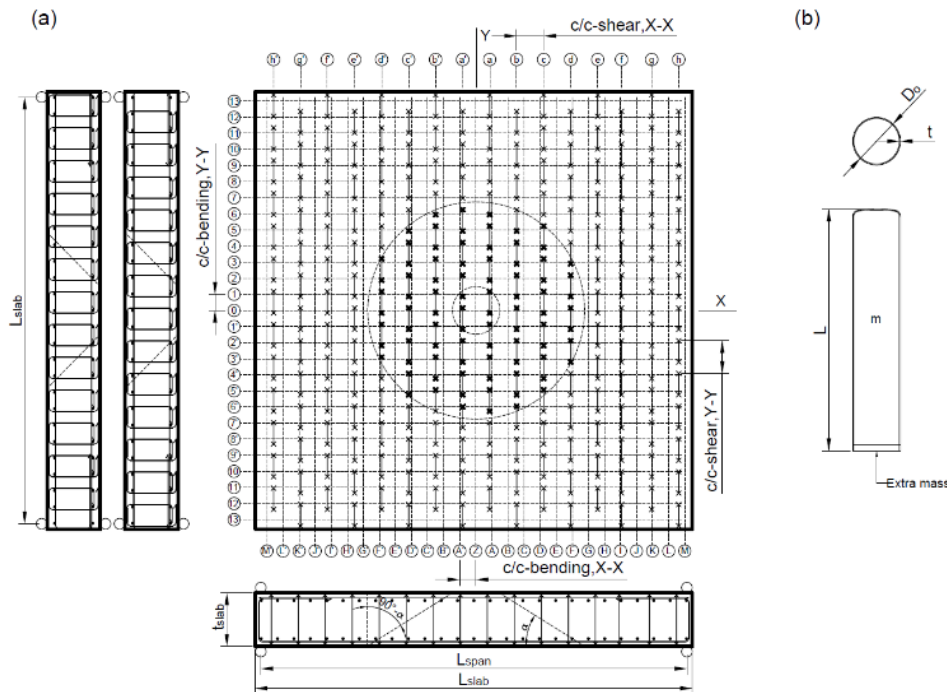


Figure 2. Drawing of (a) target slab and (b) semi-rigid projectile.

Figure 2 shows the reinforcement layout of the target slab and the shape of the projectile. The target slabs in both scales are reinforced with bending reinforcement on both sides (front and rear) and in both directions (X-X and Y-Y). Shear reinforcement is implemented using closed stirrups, which are placed in a checkerboard pattern. The stirrup spacing in the Y-Y direction follows always the spacing of the bending reinforcement, which are oriented in the X-X direction. The stirrup spacing in the X-X direction can be chosen independently. The reinforcement steel spacing has been chosen in such a way that the shear reinforcement cross-sectional area per unit of area (A_{sv}) and the bending reinforcement cross-sectional area per unit of length (A_{sb}) are both scaled according to the geometric scaling rules. Projectile outer diameter and thickness are adjusted to the geometric scaling laws by turn-removing extra steel in the manufacturing phase. To determine the material parameters, standardized material tests are carried out. For concrete, the material test results are shown in Table 2 and for steel in Table 3.

Table 2: Concrete material parameters summary table.

C40/50 concrete at 159 days. Reference impact test at 109 days, scaled impact test at 130 days.	Mean value \pm std. deviation
Compressive strength (f_{cm}) (lateral pressure 0%)	58.9 \pm 2.12 MPa
Compressive strength (f_{cm}) (lateral pressure 50%)	115 \pm 2.06 MPa
Compressive strength (f_{cm}) (lateral pressure 100%)	185 \pm 14.7 MPa
Modulus of elasticity, stabilized (E_{cm})	30.9 \pm 0.7 GPa
Poisson ratio, stabilized	0.19 \pm 0.002
Split tensile strength ($f_{ctm,sp}$)	4.26 \pm 0.67 MPa
Flexural tensile strength ($f_{ctm,fl}$)	3.28 \pm 0.03 MPa
Tensile fracture energy (G_{frac})	119 \pm 25.5 MPa

Table 3: Steel material parameters summary table.

	Measured quantity	Reference scale mean value \pm std. deviation	Larger scale mean value \pm std. deviation
S355 steel (projectile material)	Upper yield strength ReH	381 \pm 9.4 MPa	396 \pm 18.3 MPa
	Tensile strength Rm	538 \pm 1.3 MPa	531 \pm 2.0 MPa
	Elongation at rupture A	14.5 \pm 2.2 %	15.2 \pm 0.2 %
B500B bending reinforcement steel	Proof strength Rp0.2	549 \pm 2.0 MPa	522 \pm 1.9 MPa
	Tensile strength Rm	681 \pm 6.7 MPa	657 \pm 1.0 MPa
	Elongation at maximum A_{gt}	10.14 \pm 0.38 %	9.09 \pm 0.06 %
B500B shear reinforcement steel	Proof strength Rp0.2	581 \pm 6.0 MPa	538 \pm 5.4 MPa
	Tensile strength Rm	629 \pm 6.4 MPa	627 \pm 10.4 MPa
	Elongation at maximum A_{gt}	3.30 \pm 0.47 %	7.19 \pm 0.41 %

The test parameter values for the projectile and target slab are summarized in Table 4.

Table 4: Test parameters.

Test parameters	Reference test (GSX1R-S)	Scaled test (GSX1R-L)	Scaling factor	Relative difference
Projectile outer diameter, D_o / mm	222.9	390	1.75	0 %
Projectile wall thickness, t / mm	4.57	8.00	1.75	0 %
Projectile mass / kg	50.0	268	1.75^3	0 %
Slab length/width, L_{slab} / mm	2088	3590	1.72	-2 %
Slab span L_{span} / mm	2000	3500	1.75	0 %
Slab thickness, t_{slab} / mm	250	437.5	1.75	0 %
Slab concrete cover / mm	20	35	1.75	0 %
Bending reinf. diameter \varnothing_b / mm	10	16	1.60	-9 %
Bending reinf., c/c both dir. / mm	90	132	1.47	-16%
Bending reinf. area A_{sb} / mm ² /m	873	1523	1.75	0 %
Shear reinf. diameter \varnothing_v / mm	6	8	1.33	-24 %
Shear reinf., c/c in X-X dir. / mm	180	218	1.21	-31%
Shear reinf., c/c in Y-Y dir. / mm	180	264	1.47	-16%
Shear reinf. area A_{sv} / mm ² /m ²	1745	1745	1.00	0 %

TEST RESULTS

During the impact test, impact velocity was estimated from the time measurements of the flying projectile crossing laser beams. High speed cameras recorded the impact event and provided image data for Digital Image Correlation (DIC) analyses. The test slab was instrumented with strain gauges glued on the reinforcement steel and displacement sensors attached at the back surface of the target slab. Strain gauges glued on the frame supports measured the elastic strain state of the support structure and hence gave indication on the support forces. After test, a 3D model of the deformed projectile and the target slab were made using photogrammetry software RealityCapture. Cross-sections of the tested slab were obtained using diamond cut, and a 3D model of the section cuts was made using photogrammetry.

Test results are summarized in Table 5. The results show that the loading obtained from the projectile follows the geometric scaling rules. Indeed, in both scales the failure mechanism of the projectile is circular plastic folding, and hence the measured maximum force is scalable. As previously stated, strain rate sensitivity in metals induce size-effect, which is observed in the impact duration time. The measurements on the target slab, on the other hand, show that there is sensitivity to the scale factor, in particular for the permanent deformation parameters (tunnelling depth and back face deformation) and concrete scabbing measurements. Figures 3 and 4 show the orthoprojections of tested projectile and tested reinforced concrete slab. Figure 5 shows the orthoprojection of the tested slabs section cuts. The shear cone angle and shear reinforcement activation is different, as pointed out in Table 5.

Table 5: Test results summary table.

Test measurements	Reference test (GSX1R-S)	Scaled test (GSX1R-L)	Scaling factor	Relative difference
Maximum force from DIC / kN	1428	4555	1.79 ²	4 %
Impulse from DIC / kNs	6.84	36.8	1.75 ³	0 %
Impact velocity from lasers / m/s	143.2	142.8	1.00	0 %
Impact duration from video / ms	6.40	16.0	2.50	43 %
Projectile shortening / mm	445	788	1.77	1 %
Scabbed/loose concrete area / m ²	0.13	0.61	2.172	53 %
Scabbed concrete mass / kg	4.8	67	2.413	160 %
Crater/tunnelling depth / mm	29	79	2.72	56 %
Maximum back face deformation / mm	40	87	2.18	24 %
Shear cone angle	45°	58°	N/A	N/A
Activated shear rebar area $A_{sv,ac}$ / mm ²	735	4323	2.42	92 %
Shear cone area A_{cone} / mm ²	525260	2826698	2.32	76%
$A_{sv,ac}/A_{cone}$ / mm ² /mm ²	0.00140	0.00153	1.09	9%

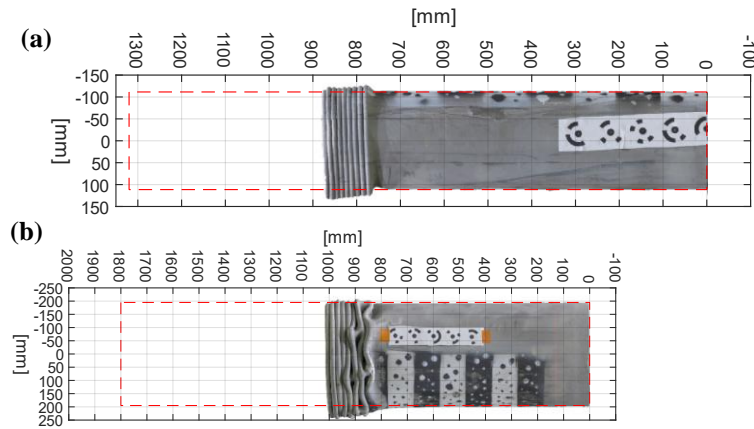


Figure 3. Orthoprojection of tested projectile (a) reference scale and (b) larger scale.

Figure 6 shows the size-effect plots of measured quantities (strains on reinforcement, displacement and permanent deformation) on normalized logarithmic scale. The measured results are given at two different locations on the horizontal axis, which corresponds to the scale factors 1.00 and 1.75. For the scale factor 1.75 the measurement at various locations gives slightly different values for the normalized response, which can be seen as scattering of the data points. The linear fit through the data points, however, averages out the scattering. Most of the measurements show positive size-effect (i.e. larger scale relatively weaker) when comparing the linear fit to the line corresponding to the geometric scaling rules. For phenomena involving strong non-linearities, such as permanent deformation, residual strain and residual displacement, this size-effect is very clear, indeed.

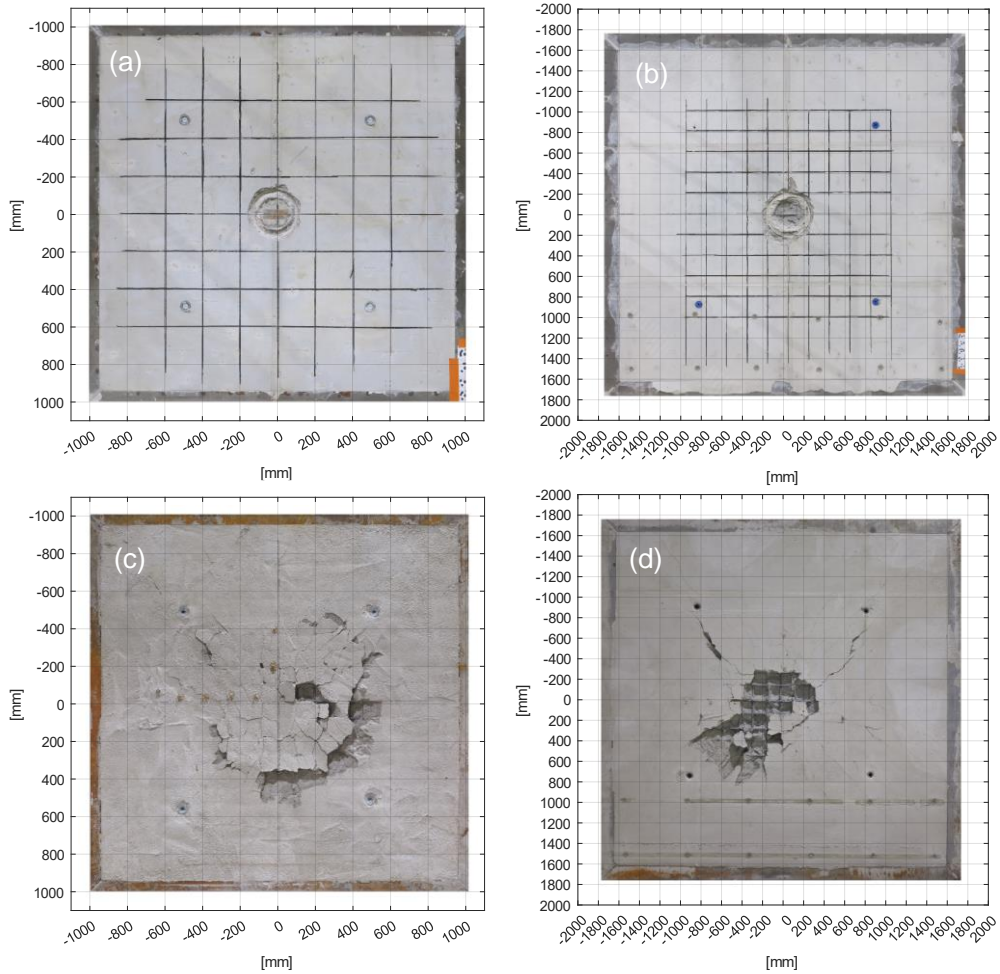


Figure 4. Orthoprojection of tested slab (a) reference scale front surface, (b) larger scale front surface, (c) reference scale back surface and (d) larger scale back surface.

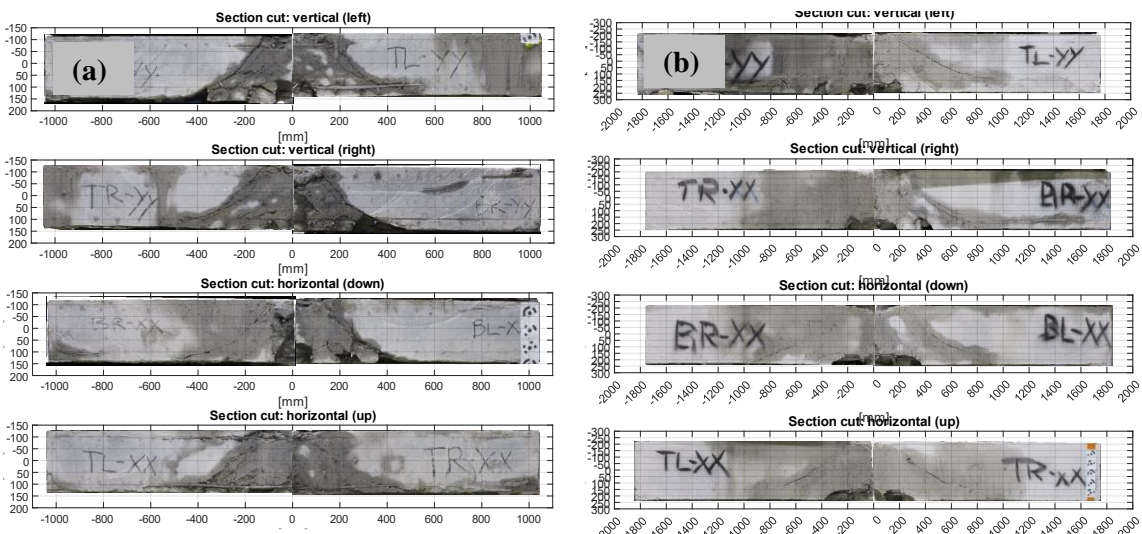


Figure 5. Orthoprojection of section cuts (a) reference scale and (b) larger scale.

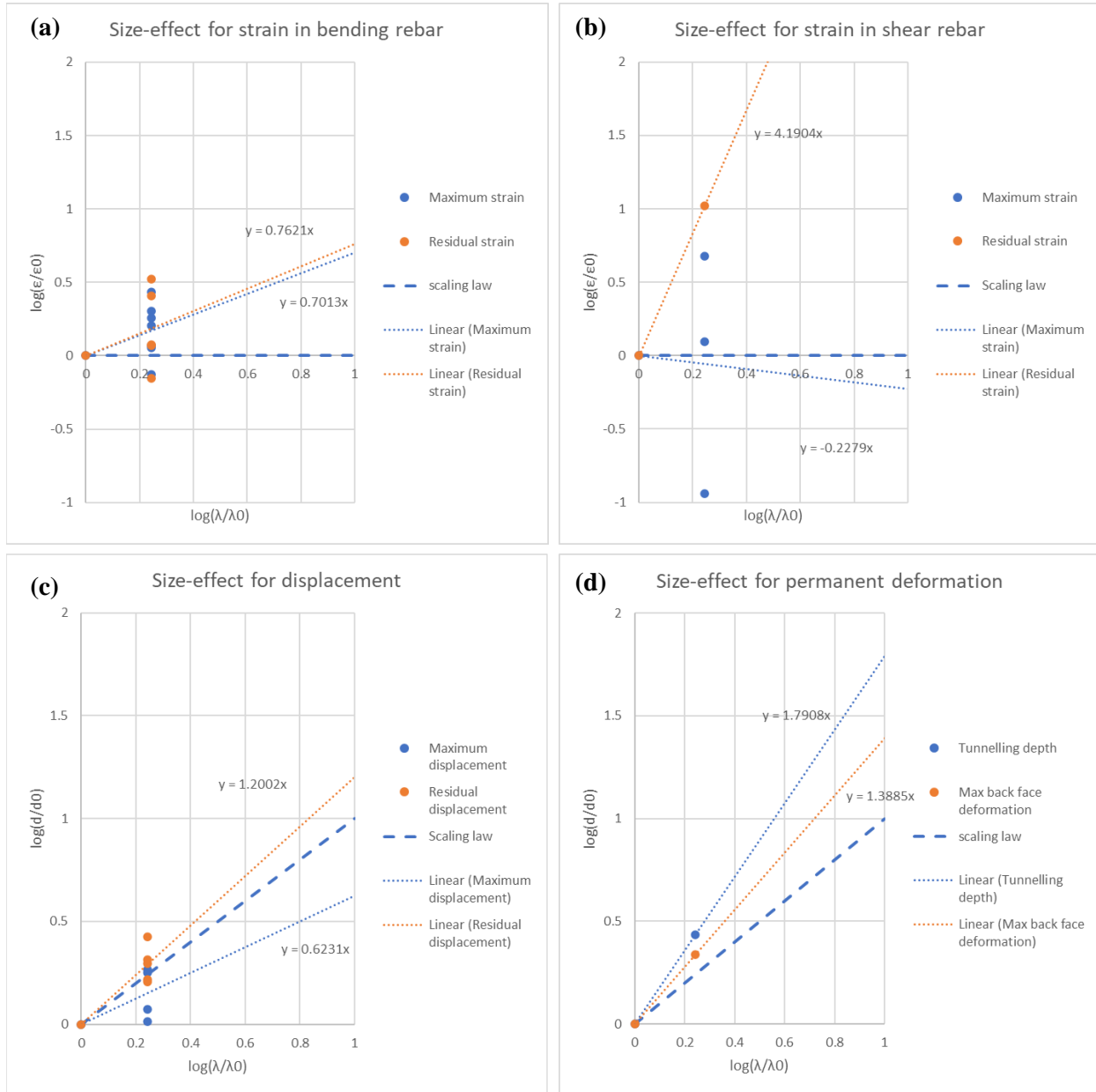


Figure 6. Size-effect plots (a) strains on bending reinforcement (b) strains on shear reinforcement, (c) displacements of back surface and (d) permanent deformation.

CONCLUSION

Two geometrically scaled reinforced concrete slabs, a $2\text{ m} \times 2\text{ m}$ small reference slab and a $3.5\text{ m} \times 3.5\text{ m}$ upscaled large slab (scale factor of 1.75), were subjected to impacts of semi-rigid projectiles with targeted impact velocities of 143 m/s. The realized impact velocity in both tests was very close to the targeted impact velocity. The expected failure mode of the target slabs was a combined punching and bending behaviour. The projectiles in both slab tests undergone plastic folding, which ensures a scalable loading force for test measurement comparison. Most of the measured response quantities of the target slab indicated the presence of size-effect.

To make solid claims about the size-effect based on experimental results, one needs test repetitions in order to assess the statistical significance of the observations. Indeed, slight variations in design parameters may affect the entire outcome of the size-effect study. It was previously noticed that fracture of the projectile is a stochastic process: there is a higher probability for larger projectiles to fracture than for smaller ones. Since fracture dissipates less energy than a plastic folding mechanism, there is a higher probability that the loading force created by a larger projectile is relatively weaker than the loading force of the smaller projectile. Both reference and larger scale projectiles did not fracture, which resulted in a scalable loading force. Based on the results shown in this article, it could be concluded that the target slab response shows a measurable size-effect. This size-effect indicated that larger target slabs are relatively weaker (suffered larger damage) than the smaller ones when loaded with an impact load that follows the geometric scaling rules. However, this preliminary conclusion might be an exception if it turns out from the statistical analysis that the likelihood for projectile fracture at larger scales is important. Furthermore, additional tests with a similar setup are needed to confirm the scale effects.

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