

IMPACT LOADED REINFORCED CONCRETE SLABS IN COMBINED PUNCHING AND BENDING DAMAGE SCENARIO: NUMERICAL EVALUATION OF THE SIZE-EFFECT USING THE SOFiSTiK LAYER MODEL

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ABSTRACT

The main objective of the current fourth phase of the multinational research project IMPACT (organised by the VTT Technical Research Centre of Finland and funded by several institutions including the Swiss Federal Nuclear Safety Inspectorate ENSI) is to analyse the influence of the test scaling on the various phenomena observed in the previous project phases. Therefore, the IMPACT IV test program includes impact tests on larger and thicker reinforced concrete slabs.

The first geometrically scaled tests of reinforced concrete (RC) slabs impacted by deformable projectiles were conducted to investigate the combined effect of bending and punching when approaching the ultimate load capacity. Nonlinear finite element (FE) simulations of these tests using the structural analysis software SOFiSTiK (2024) were reported by Borgerhoff et al. (2024). The dimensions of the geometrically scaled slabs were enlarged by a scaling factor of $\lambda = 1.75$ from a clear span of 2.0 m by 2.0 m for the small slab to 3.5 m by 3.5 m for the large one. Fedoroff et al. (2024) reported severe damage and predominant punching shear failure of the slabs for the first geometrically scaled test set so-called GSX1, which led to insufficient measurement data for the evaluation of scale sensitivity. The likely cause for this unexpected behaviour appears to be a change in the deformation and fracture characteristics of the projectiles. In particular, the use of carbon steel instead of stainless steel and the absence of longitudinal cracks apparently lead to a stiffer impact behaviour of the GSX1 projectiles and thus to higher impact loads.

Based on these findings, the GSX1 test set, consisting of the small-scale reference test and the geometrically upscaled test, is retaken using carbon steel projectiles with smaller wall thickness and thus lower stiffness, resulting in smaller impact loads. This paper reports on the nonlinear numerical simulations of the newly retaken scaling test set, so-called GSX1R, using the SOFiSTiK software. Additionally, a numerical investigation with variation of the scaling factors is carried out to investigate the influence of the discretization on the size-effect using FE methods for simulating the combined bending and punching response of RC slabs subjected to impact loading.

INTRODUCTION

In Phase IV of the research project IMPACT, experimental studies are carried out with semi-rigid projectiles impacting geometrically scaled RC slabs, which are designed to exhibit a combined bending and

punching behaviour when approaching the ultimate impact load capacity. A set of two experiments consists of an RC slab with a span of 2.0 m x 2.0 m, which represents the reference test, and an upscaled RC slab with a span of 3.5 m x 3.5 m, which is thus enlarged by the scaling factor $\lambda = 1.75$.

The first geometrically scaled combined bending and punching test GSX1 resulted in projectiles penetrating significantly beyond the concrete cover with associated detachment of a punching cone and severe spalling as reported by Fedoroff et al. (2024) and Borgerhoff et al. (2024). Since the unexpectedly large displacements around the punching cone exceeded the measuring capacity of the sensors, a reliable statement on scalability based on the GSX1 test set consisting of GSX1-S (small slab) and GSX1-L (large slab) was hardly possible. Since the impact forces of the carbon steel projectiles were significantly higher than those of the stainless-steel projectiles used in the previous phases of the IMPACT project, the GSX1 test was retaken under the designation GSX1R with reduced wall thickness of the carbon steel projectiles to achieve lower impact forces and thus avoid excessive damage as observed in the GSX1 tests. This paper describes the nonlinear FE simulations of the GSX1R slab tests using the SOFiSTiK software (2024).

DESIGN OF THE GSX1R TEST

The dimensions of the RC slabs of the GSX1R test set and their reinforcement largely correspond to those of the GSX1 test set described in Borgerhoff et al. (2024). Only the bending reinforcement of the scaled test GSX1R-L is slightly reduced to exactly achieve the scaling factor of 1.75, see Table 1 and Figure 1. The new optimised values, which slightly differ compared to the GSX1-L test are shown with a bold font in the table.

Table 1. Dimensions and reinforcement of the RC slabs of the GSX1R test set.

Test		Small scale test GSX1R-S	Large scale test GSX1R-L
Slab thickness	[m]	0.25	0.438
Concrete cover	[m]	0.020	0.035
Slab dimensions	[m]	2.088	3.590
Span width	[m]	2.00	3.50
Scaling factor dimensions		1.00	1.75
Bending reinforcement		Ø10 mm, c/c 90 mm ewef*	Ø16 mm, c/c 132 mm ewef*
	[cm ² /m]	8.73	15.23
Scaling factor reinforcement		1.00	1.75
Shear reinforcement type		closed stirrups	
Shear reinforcement		Ø6 mm, c/c 180 mm	Ø8 mm, c/c 218/264 mm
	[mm ² /m ²]	17.45	17.47
Scaling factor		1.00	1.00

*ewef = each way each face (in both directions and on both sides)

The main geometric changes compared to the GSX1 test set were made to the carbon steel projectiles. The wall thickness was reduced to such an extent to promote shear cracking and nonlinear strains in both the longitudinal and shear reinforcement, but to prevent penetration of the projectile with excessive displacement of the punching cone. In addition, minor adjustments of the outer projectile diameters were made to exactly achieve the scaling factor of 1.75, see Table 2 (optimised dimensions shown with a bold font in the table).

Table 2. Data of the projectiles of the GSX1R test set.

Test		GSX1R-S	GSX1R-L	Scaling factor
Material		S355J2H	S355J2H	
Diameter	[mm]	222.9	390.0	$\lambda = 1.75$
Wall thickness	[mm]	4.57	8.00	$\lambda = 1.75$
Projectile mass	[kg]	50	268	$\lambda^3 = 5.36 (\lambda = 1.75)$
Impact velocity	[m/s]	143	143	$\lambda = 1.00$

NUMERICAL SIMULATIONS OF THE GSX1R TEST SET

The GSX1R test set was numerically simulated by nonlinear dynamic FE analyses using the implicit solver of the structural analysis software SOFiSTiK (2024). The results of these simulations are compared with the measured results to assess the scaling sensitivity of the tests and to confirm the predictive quality of the numerical simulations.

Modelling

The three-dimensional (3D) FE models of the RC slabs in the test facility contain the enclosing steel frame and the supporting backpipes, see Figure 1. The slabs are modelled with multi-layered shell elements, which comprise a nonlinear material model of reinforced concrete. The supporting steel structure is modelled using beam elements. Further information on the layered shell model in SOFiSTiK (2024) can be found in Borgerhoff et al. (2024).

The impacting projectiles are not explicitly represented in the SOFiSTiK models. Instead, separately calculated impact load time histories are applied to the decoupled model of the RC slabs.

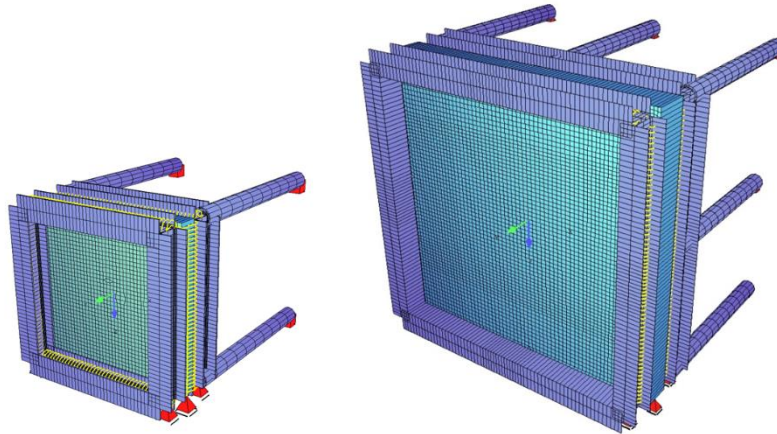


Figure 1. FE models of the reference test GSX1R-S (left) and the upscaled test GSX1R-L (right).

Material Properties

Since no specific material properties were yet available for the numerical simulations of the GSX1R test, the values obtained from the GSX1 test material samples were used for the numerical representation of concrete and steel. The assumptions for the concrete C40/K50 apply to both slabs GSX1R-S and GSX1R-L,

since they were manufactured from the same concrete batch, see Table 3. The material properties of the reinforcing steel B500B were determined for reinforcement diameters of 10 and 16 mm (longitudinal reinforcement) and 6 and 8 mm (shear reinforcement), see Table 4. The material testing for the projectile steel S355J2H resulted in a yield strength of $R_{eH} = 370$ MPa, a tensile strength of $R_m = 533$ MPa and an ultimate elongation of 27.7 %.

Table 3: Properties used for concrete material model.

Compressive strength f_{cm}	[MPa]	63.3
Tensile strength f_{ctm}	[MPa]	4.29
Young's modulus E_{cm}	[MPa]	33900
Fracture energy G_F	[N/m]	129

Table 4: Properties used for material model of the reinforcing steel.

Reinforcement direction (related to the slab surface)		longitudinal	transverse
Proof strength $R_{p0.2}$	[MPa]	514 - 538	525 - 573
Tensile strength R_m	[MPa]	598 - 658	612 - 648
Total elongation under maximum load A_{gt}	[%]	8.5 - 11.0	2.67 - 8.75

Loads Caused by the Impacting Projectiles

The force-time histories caused by the impact of the semi-rigid projectiles on the centre points of the RC slabs were determined using the Riera method according to Riera (1968). The force-time functions for the two tests GSX1R-S and GSX1R-L are shown in Figure 2. By reducing the projectile stiffness, the average impact forces drop to approx. 60% of the values in the GSX1 test.

For the circular loading area in the FE model, a diameter expansion of approx. 10% due to the folding of the projectiles and a load distribution at an angle of 45° from the slab surface to the centre plane of the slab (shell element surface) is considered.

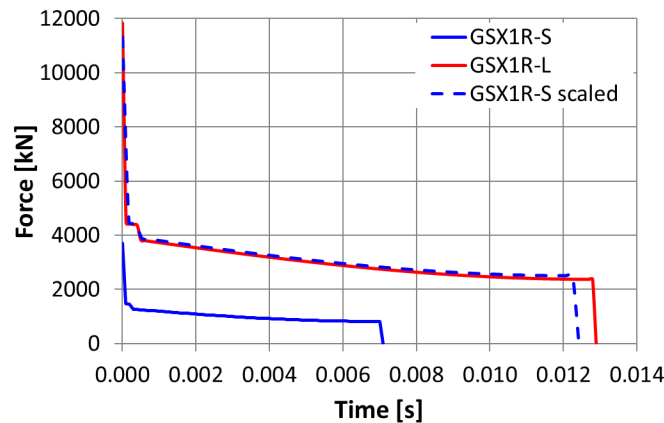


Figure 2. Force-time functions of the GSX1R test set (dashed line scaled with $\lambda = 1.75$)

Results of the Numerical Simulations

Nonlinear time step calculations for a total duration of 120 ms are carried out for the reference test GSX1R-S and the scaled test GSX1R-L. The first 20 ms were calculated with a time step of 0.02 ms, after which a time step of 0.1 ms was used. In addition to the damping resulting from the nonlinear effects, a numerical Rayleigh damping was considered, the parameters of which were adjusted to 1% of critical damping for a frequency range of 30 to 80 Hz.

Scaling insensitivity is given when the displacements of the upscaled test GSX1R-L agree with the results of the reference test GSX1R-S multiplied by the scaling factor $\lambda = 1.75$. Figure 3 shows that the displacements in the GSX1R-L test are larger than the scaled displacements of GSX1R-S. The largest deviations occur in the central region of the slab, where the impact causes the greatest plastic deformations.

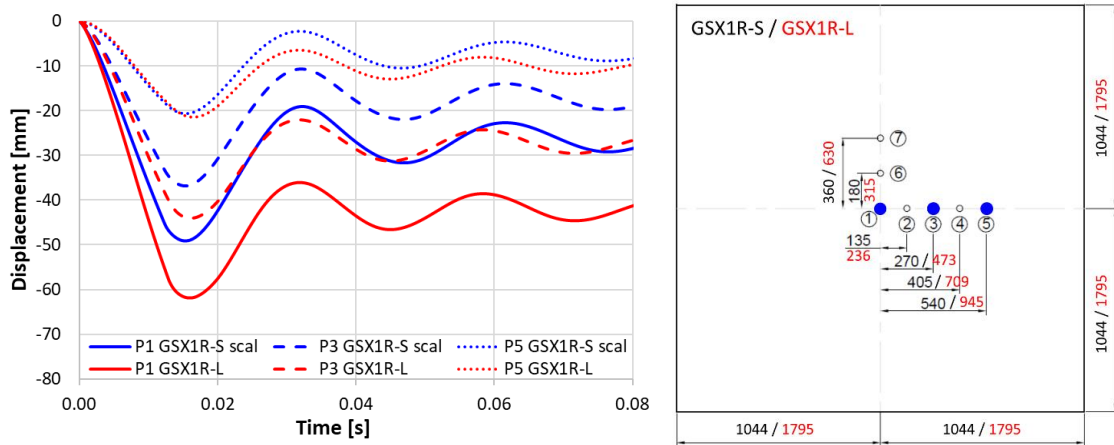


Figure 3. Calculated displacements in the tests GSX1R-S (scaled) and GSX1R-L.

Figure 4 shows the calculated mean strain-time histories of the bending reinforcement on the backside of the slab for two sensor positions on the horizontal reinforcement (B1 and B7) and two sensors on the vertical reinforcement (B2 and B4). Significant deviations can be observed at the central region of the slab similar to the displacement results. Outside this zone, the strains largely agree (gauges B7 and B4).

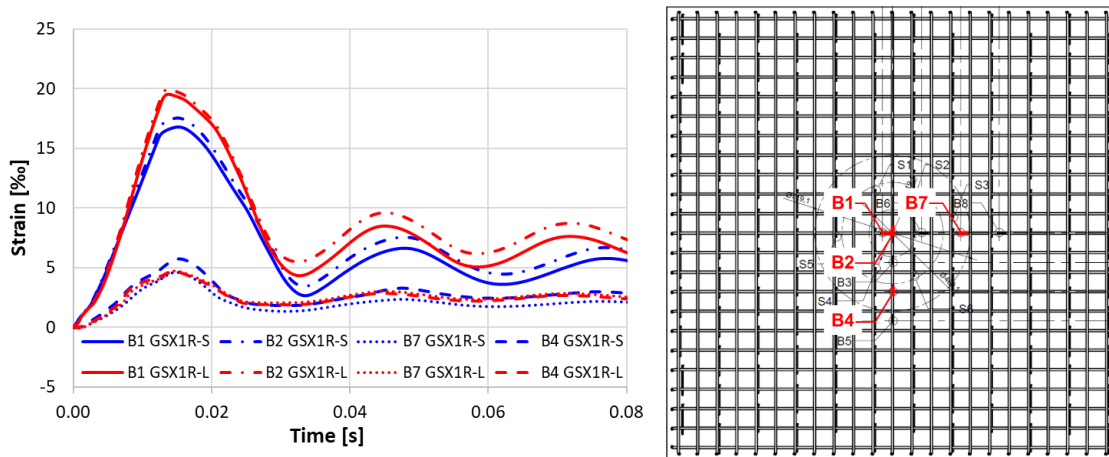


Figure 4. Calculated mean strains of the bending reinforcement in the tests GSX1R-S and GSX1R-L.

Figure 5 shows the sums of the calculated support forces of the 4 (GSX1R-S) and 8 (GSX1R-L) backpipes of the supporting steel frame of the impact test facility over time. The calculated support forces of the GSX1R-L test are, to a limited extent, smaller than the calculated scaled values of the GSX1R-S test, probably due to the different number of supporting backpipes (Figure 1), resulting in a larger support stiffness for GSX1R-L. In addition, the time history of the GSX1R-L test shows a superimposed harmonic corresponding to different support systems.

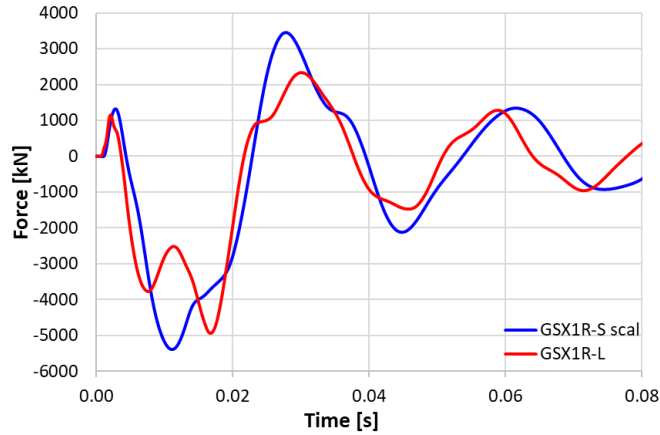


Figure 5. Calculated sums of support forces in the tests GSX1R-S (scaled) and GSX1R-L

The numerically determined size-effect has not fundamentally changed compared to the calculated results of the GSX1 test, cf. Borgerhoff et al. (2024). The displacements and the strains of the bending reinforcement are reduced to approx. 90% and the support forces to approx. 85% of those of the GSX1 test. However, the deviations between the scaled results of the reference test (-S) and the results of the upscaled test (-L) differ from each other to almost the same extent for GSX1 and GSX1R.

Comparison of the Numerical Simulation Results and the Measured Test Data

The results of the retaken test set GSX1R are presented in the conference paper by Fedoroff et al. (2025). The tested slabs show concrete spalling on the frontside without any clear penetration of the projectile and only partly detached scabbing of the concrete cover on the backside. A clear punching cone was formed in both tested slabs.

Figures 6, 7 and 8 compare calculated and measured results of the GSX1R test set. The positions of the compared displacement sensors and strain gauges are shown in Figures 3 and 4. The displacement sensors provided reliable results except for the sensor in the centre of the slab, which was affected and loosened by concrete spalling, see Figure 6. In both tests, the maximum measured displacements exceed the calculated values, while the residual displacements are largely consistent. The comparatively stronger oscillations in the measurements of the larger slab (GSX1R-L) likely indicate a lower damping of the slab.

The measured steel strains in the sensor positions P1, P3, and P5 according to Figure 4 are also generally larger than the calculated values, especially the permanent plastic strains in the centre of the slab, see Figure 7. The latter is probably due to the loss of bond between concrete and plastic deformation of reinforcement in this area, which is not adequately captured in the layered shell model in SOFiSTiK.

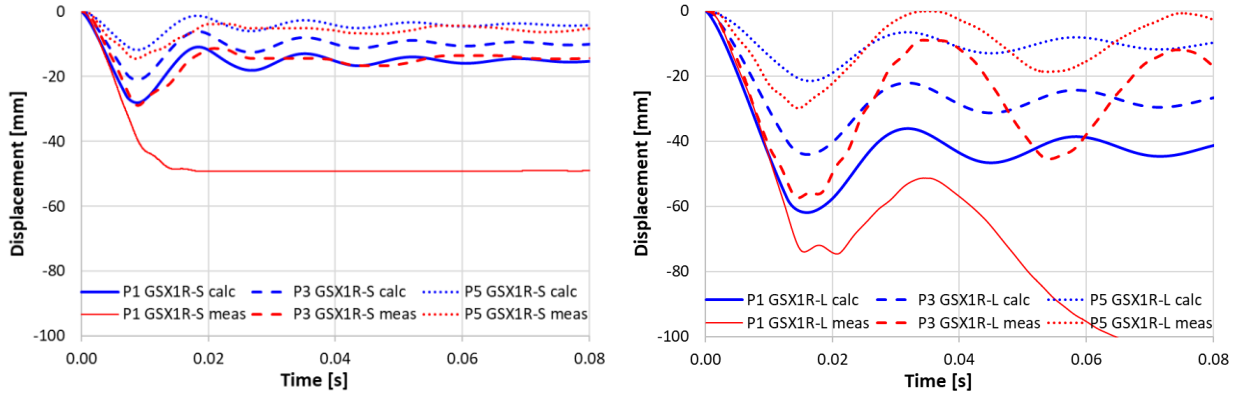


Figure 6. Calculated and measured displacements in the tests GSX1R-S (left) and GSX1R-L (right).

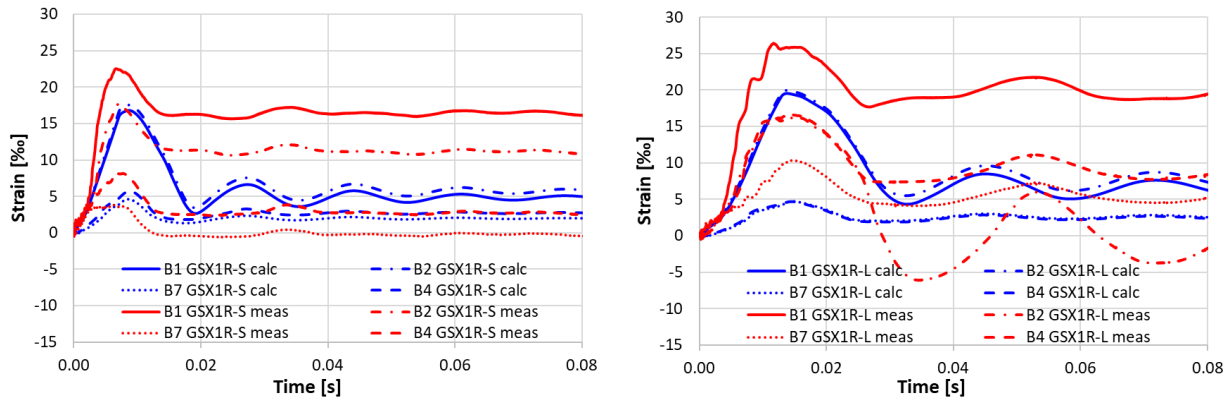


Figure 7. Calculated and measured mean strains of bending reinforcement in the tests GSX1R-S (left) and GSX1R-L (right).

The measured support forces are on average approx. 40% higher in the GSX1R-S test and approx. 50% higher in the GSX1R-S test than the calculated ones, see Figure 8. The reason for this is probably the simplified modelling of the test frame with beam elements without considering the stiffening components.

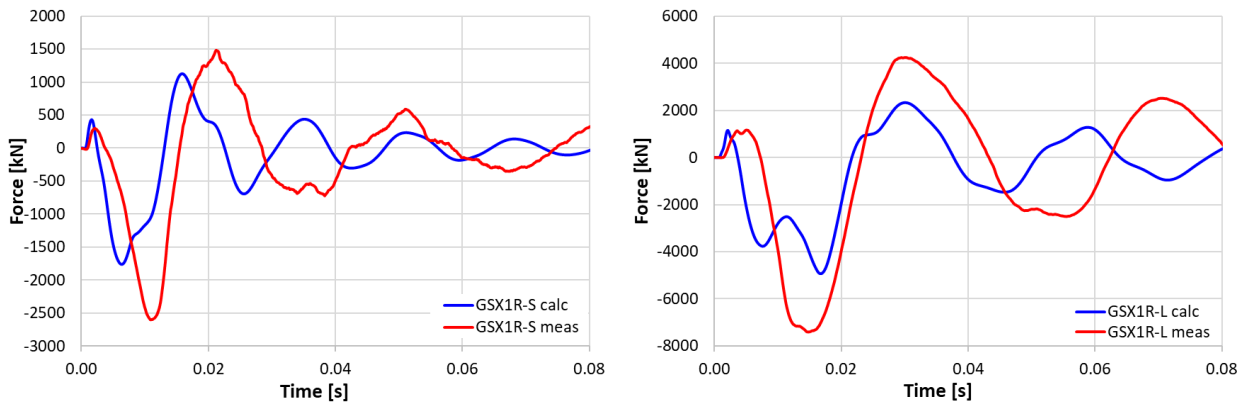


Figure 8. Calculated and measured sums of support forces in tests GSX1R-S (left) and GSX1R-L (right).

Assessment of the Size-Effect Based on the Experiments

To assess the scaling sensitivity based on the experimental results, the scaled displacement, steel strain and support force time histories in test GSX1R-S are compared with the results in test GSX1R-L in Figures 9 and 10. Apart from the less damped displacement oscillations in the GSX1R-L test, these results prove to be only slightly sensitive to scaling, see Figure 9 on the left. Even from the time histories of the steel strains in Figure 9 on the right, no size-effect can be reliably derived if local discontinuities in the bond behaviour of the reinforcement in connection with the positions of the strain gauges are considered.

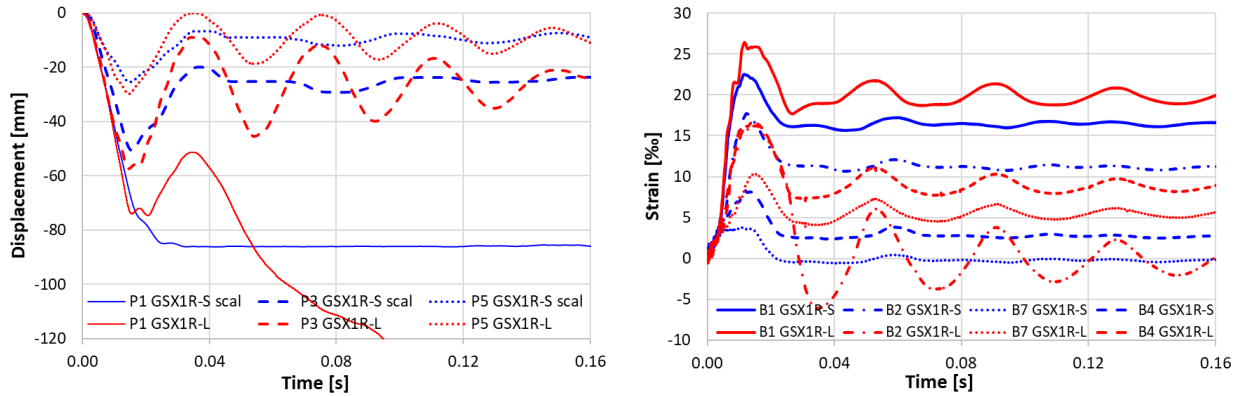


Figure 9. Measured displacements (left) and mean strains of bending reinforcement (right) in the tests GSX1R-S (scaled) and GSX1R-L.

The measured sums of the support forces in Figure 10 show a good agreement between the results of the GSX1R-L test and the scaled results of the GSX1R-S test, considering the structural differences between the two test frames. From these results, it can be concluded that the support reactions are scalable.

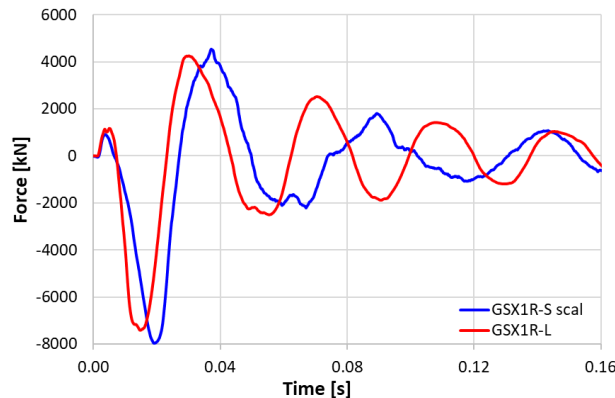


Figure 10. Measured sums of the support forces in the tests GSX1R-S (scaled) and GSX1R-L.

Numerical Size-Effect Study Based on the Test GSX1R-S

An additional numerical investigation of the geometrically scaled combined bending and punching test GSX1R with variation of the scaling factors is carried out to investigate the influence of the FE mesh on the size-effect. Based on the GSX1R-S test simulation as reference test, in addition to the scaling with the factor $\lambda = 1.75$, the scaling factors $\lambda = 0.5$ and $\lambda = 5.0$ are included in the parametric study. It is assumed that the mesh size either remains constant (variant 1) or changes linearly (variant 2) depending on the scaling factor λ . All dimensions of the concrete slab, the reinforcement ratio and the projectile as well as

the dimensions and cross-sectional values of the steel frame and the backpipes are scaled in the FE model in an exact manner. The force-time function of the GSX1R-S test ($\lambda = 1.0$) shown in Figure 2 is also precisely scaled. Therefore, any observed size-effect refers only to the RC slab and not to the projectile.

The parametric mesh size study shows a high degree of agreement between the displacements and the support forces in the mesh size variants 1 and 2. However, considerable differences are observed, particularly in the residual plastic strains of the reinforcing steel. The FE model discretized with a finer mesh leads to higher strains.

The evaluation regarding the numerical scale sensitivity is carried out based on the parametric calculations for variant 2 (mesh size linearly dependent on λ). The size-effect is illustrated and quantified using the diagrams in Figures 11, 12 and 13. The diagrams show the logarithm of the quotient of the displacements, steel strains and support forces calculated for λ and $\lambda_{ref} = 1.0$ over the logarithm of λ . An exact scaling without size-effects is given if the quotient of the forces at λ and λ_{ref} is equal to λ^2 , the quotient of the displacements at λ and λ_{ref} is equal to λ and the strains are independent of λ . Figures 11 and 12 show that the significant size-effect on the displacements decreases from the slab centre towards the slab edge. The size-effect on the support forces is quite small with a deviation of 6%.

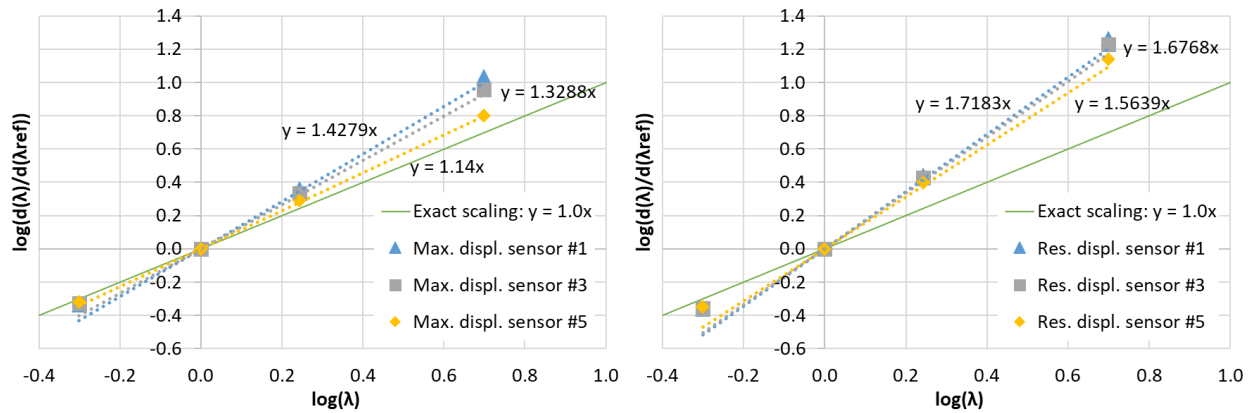


Figure 11. Logarithmic deviations of maximum and residual displacements from exact scaling.

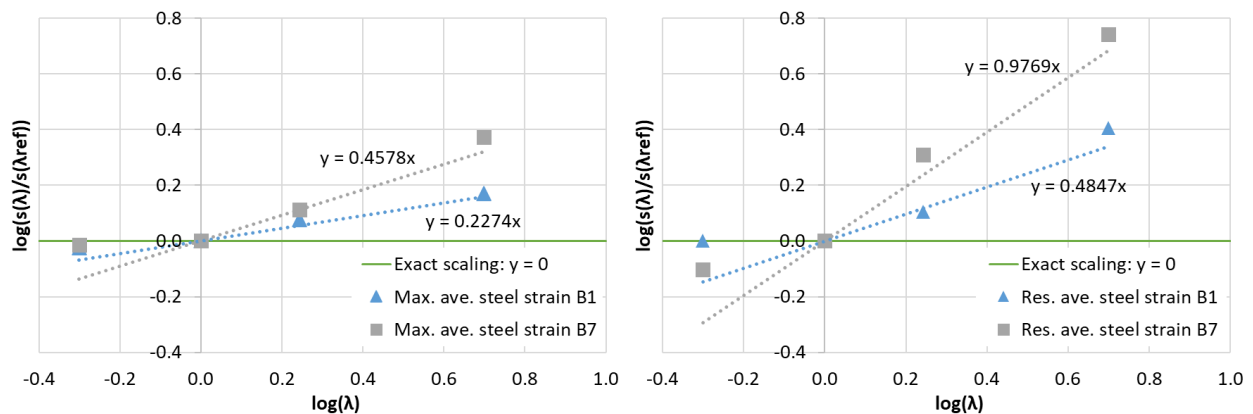


Figure 12. Logarithmic deviations of maximum and residual mean steel strains from exact scaling.

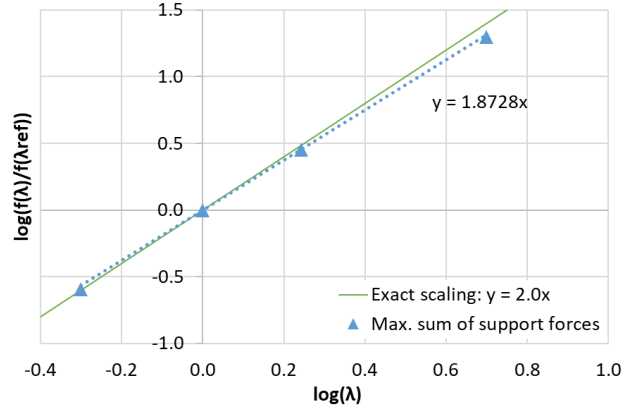


Figure 13. Logarithmic deviations of sums of support forces from exact scaling.

CONCLUSION

FE simulations of the repeated geometrically scaled test set were performed using the SOFiSTiK software to investigate the extent of the size-effect in RC slabs subjected to the impact of deformable projectiles under combined bending and punching behaviour. The numerical simulation of the GSX1R test set using a scaling factor of $\lambda = 1.75$ shows that the displacements and reinforcement strains in the nonlinearly deformed central region of the test slabs are subject to a stronger size effect than the rest of the slab. However, the measured maximum displacements and reinforcement strains, which exceed the calculated results, prove to be only slightly scaling sensitive when comparing the reference test and the scaled test. The analytically obtained as well as the measured time histories of the impact forces and the support reaction forces were scalable.

A supplementary numerical parameter study including the two additional scaling factors $\lambda = 0.5$ and $\lambda = 5.0$ show the existence of a size-effect and a mesh-size dependency. According to the investigations, the size-effect on the displacements is more pronounced, especially in the centre of the plate, where the largest plastic deformations are observed.

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