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EFFECT OF IMPACT LOCATION ON THE PUNCHING SHEAR RESISTANCE OF A CONCRETE WALL: NEAR EDGE IMPACT TEST

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ABSTRACT

This paper aims to verify the effect of so-called arching action also for dynamically loaded slabs. Due to the arching action, part of the shear force caused by concentrated loading applied close to linear support is transmitted to this support through a compression strut. This in turn increases the shear strength at the critical region. This plays a role also when analyzing an airplane crash against a concrete structure like a nuclear power plant (NPP) reactor building. As semi-rigid projectiles, the engines cause considerable shear forces with shear failure as the extreme outcome. To study this situation empirically, a so-called near edge (NEX) test was designed and carried out in which a semi-rigid projectile was impacted against a concrete wall near moment transferring junction with supporting side walls. This test was performed as part of the fourth phase of IMPACT program (IMPACT IV – NEREID project), which is organized by VTT Technical Research Centre of Finland. The outcome of the test was compared against a similar reference test (X4) from a previous phase of the IMPACT program (IMPACT III project) without support walls. While perforation was reached in test X4, the punching capacity of the front wall in test NEX was not exceeded.

INTRODUCTION

Airplane crash impact can result in a shear failure of a reinforced concrete (RC) structure, like an NPP building in the extreme case. While the shear forces acting on a cross-section under concentrated loading theoretically increase when this loading is applied closer to the supports, part of the shear force is transmitted to the supports through the compression strut. This arching action has been demonstrated for statically loaded beams without shear reinforcement for example by Kani (1966) and slabs by Natário et al (2014). This in turn increases the shear strength of the critical region more than the shear stresses are increased. Natário et al. (2014) concluded that this applies for slabs when concentrated loads are applied within a distance d – 2.75d from the face of a linear support with d being the flexural effective depth of the slab. To fulfil a gap in knowledge of the phenomenon under impact loading, a test was designed and carried out in which a projectile having considerable crushing strength impacted a RC wall near moment transferring junction with supporting rear walls.

A series of combined bending and punching behavior impact tests was carried out with VTT impact testing apparatus in a multinational research project IMPACT III (Darraba et al., 2022). The purpose of this so-called X-series was to study the relationship/interaction between the punching shear and bending damage of RC slabs under impact loading. The tested slabs were two-way supported with simple supporting and concentrated load applied mainly 4d away from the support line. The parameters that were changed between the tests included the projectile (mass, crushing strength), impact velocity, longitudinal reinforcement, shear reinforcement (type and spacing) as well as concrete strength while the impact distance from the support was kept constant. To study the one-way shear behaviour for the slabs subjected to impact loading, a test called NEX was designed by Électricité de France (EDF) in which a similar impact to the chosen reference test X4 of the project IMPACT III takes place closer to the supporting wall.

TEST SPECIMEN

Geometry and Supporting

The target structure is shown in Figure 1 and Figure 2. It includes an "impacted" front wall, which is supported at the rear side by two short walls. All the walls are constructed on a floor slab supported on four steel pedestals, which anchored to the rock below the test hall floor with anchor bars. The support walls are supported in the impact direction with 4 horizontal steel pipes. The concentrated load is applied 1.3 d (target hit area) away from the face of the support walls.

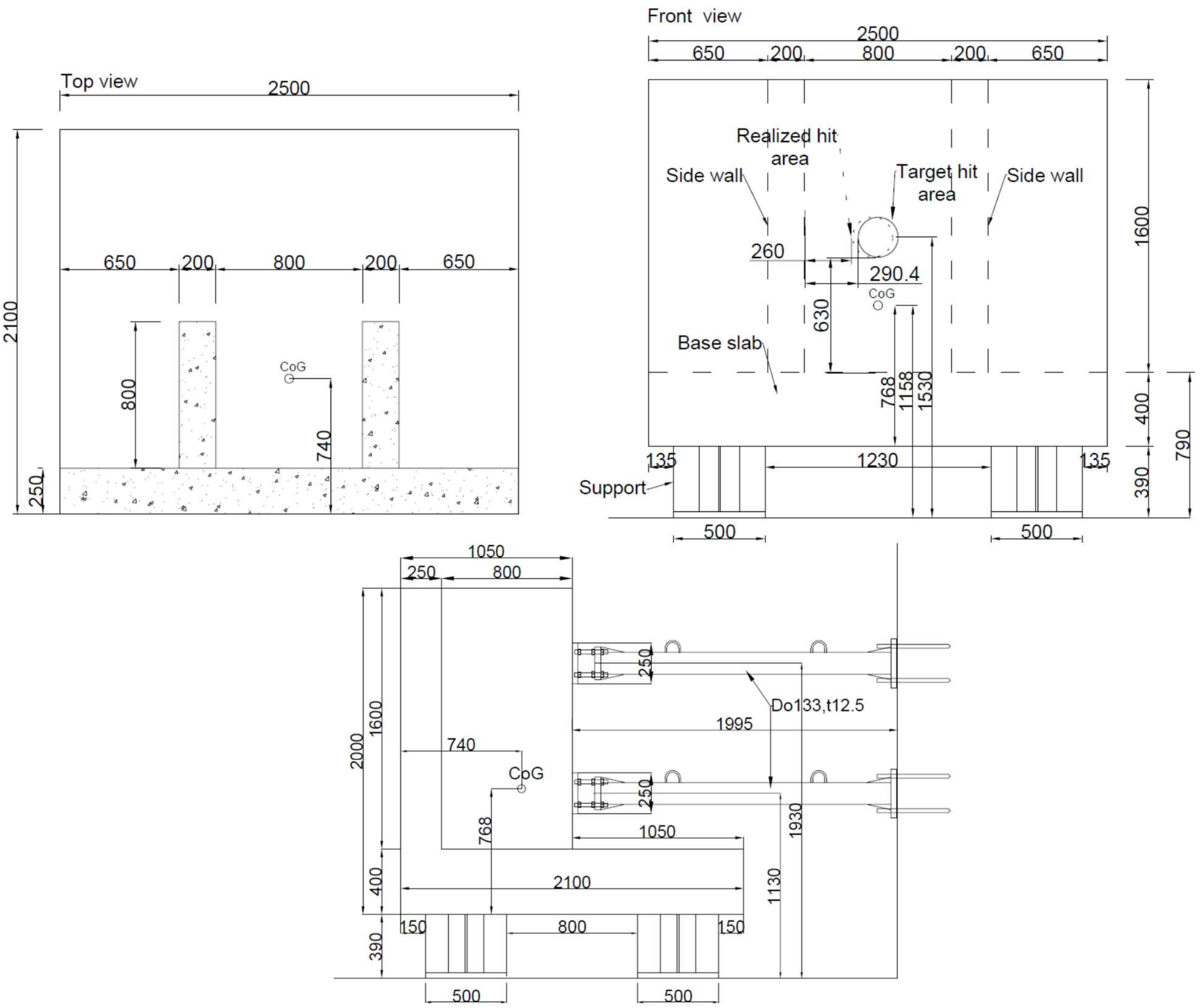

Figure 1. Test structure. Top left: Top view. Top right: Front view. Bottom: Side view.

Reinforcement

The whole structure was reinforced with B500B ribbed bars. The impacted wall was reinforced with D10 ribbed bars with spacing of 90 mm in both directions and on both faces. The horizontal bars were located closer to the surface with the concrete cover of 20 mm. In the vertical direction the bars were tied to D10 starter bars coming out of the base slab with overlapping length of 300. In the horizontal direction, the D10 bars of the support walls were continued to the impacted wall, 60 mm from the corner of the walls at the impact height and 255 mm elsewhere. The ends of the impacted wall were strengthened with D10 U-bends with 340 mm overlapping with the straight bars. Shear reinforcement was used in a form of D6 closed stirrups with staggered spacing of 360 mm in the horizontal direction and 180 mm in the vertical direction, leading to reinforcement ratio of 16.8 cm^2/m^2.

The used reinforcement batches were subjected to tensile testing. The tested quantities were the yield strength, $R_{p0.2}$, the ultimate strength, R_m, the Young's modulus, E, the total elongation A_{100}, and the elongation under maximum load, A_{gt}. All the quantities were obtained from the same test. Three samples were used for each bar size and batch. Shear reinforcement was not tested as it was considered to act only within the elastic range. The test results are compiled in in Table 1.

Table 1: Results of the tensile tests for the reinforcement bars.

Bars used for	Diameter [mm]	$R_{p0.2}$ [MPa]	R_m [MPa]	E [GPa]	A_{100} [%]	A_{gt} [%]
Walls	6	536.4	671.5	206.4	13.85	9.35
Walls	10	517.2	606.9	218.2	16.1	9.9
Base slab	10	526.2	608.9	200.4	14.5	9.5

Concrete

The structure was cast in two batches: first the floor slab and then the walls. The nominal strength class of concrete used for the structure was K50/C40, the maximum aggregate size was 8 mm and the flexibility class S4. Both batches of concrete were subjected to diverse testing, the main results of which are compiled in Table 2. The tested quantities were the unconfined, f_c. and confined, $f_{c,c50\%}$ and $f_{c,c100\%}$, compressive strength, the secant modulus, $E_{Sec.}$, the Poisson's ratio, ν and the splitting tensile strength, f_{ct}. All the quantities were tested with cylinders with height and diameter of 200 and 100 mm, respectively.

Table 2: Results of the concrete material tests.

Quantity	**Notes**	**W**	**BS**	**Unit**	**No. of samples**	**Standard/comments**
f_c (FD)	*	52.09/0.386	-	Mpa/-	3	SFS-EN 12390-3
f_c (DD)		48.89	48.92	MPa	3	SFS-EN 12390-3
$E_{Sec.}$	**	28.07/31.87	24.63/28.53	Gpa/Gpa	3	SFS-EN 12390-13
ν		0.191/0.197	0.197/0.202	-/-	3	SFS-EN 12390-13
$f_{c,c50\%}$	***	102/1.52/0.68	-	Mpa/-/-	2	Own/50% conf. ratio
$f_{c,c100\%}$		133/1.98/0.08	-	Mpa/-/-	2	Own/100% conf. ratio
f_{ct}		3.573	-	MPa	3	SFS-EN 12390-6

The abbreviations and notes used in Table 2 are as follows: BS -Base Slab, W – Walls, FD – Force Driven, DD – Displacement Driven, * - parameter value/strain at max, ** initial/stabilized, *** - parameter value/axial strain at max./circum. strain at max.

Instrumentation

The impact was documented with high-speed videos with frame rates of 3000 and 5000 fps. The structure itself was instrumented as follows:

- 16 strain gauges (Kyowa KFEL-5-120-C1L1M2R) on the reinforcement (Figure 2)
- 10 displacement sensors (OPKON SLPC 1000) (Figure 3)
- 4 horizontal support force measurements
- 4 vertical support force measurements and
- 2 laser sensors (Elektro-GmbH "Eltrotec Laser Light Barrier" series LLS12/3.0) to measure the impact velocity.

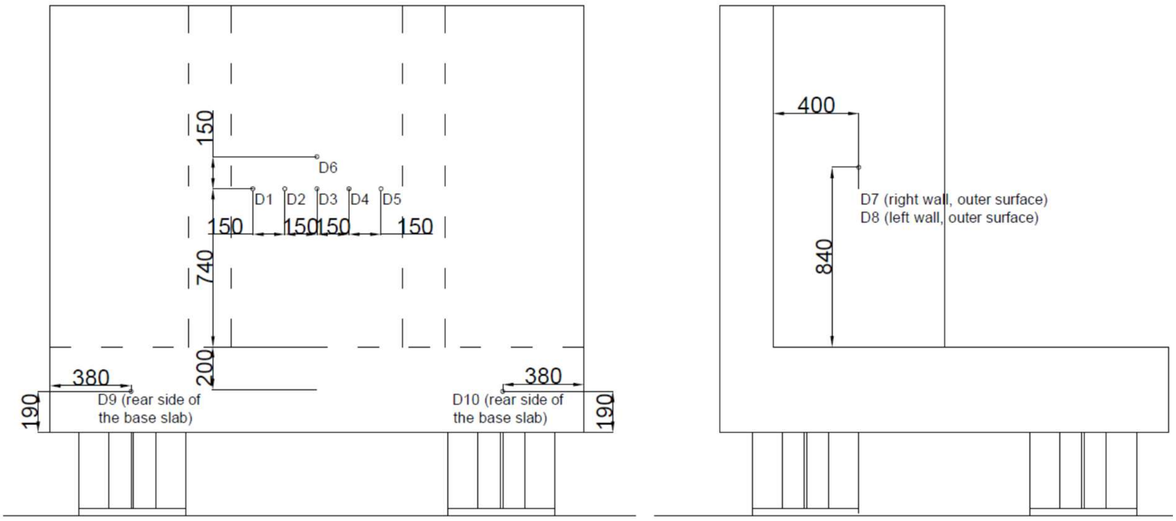

Figure 2. Locations of the displacement sensors.

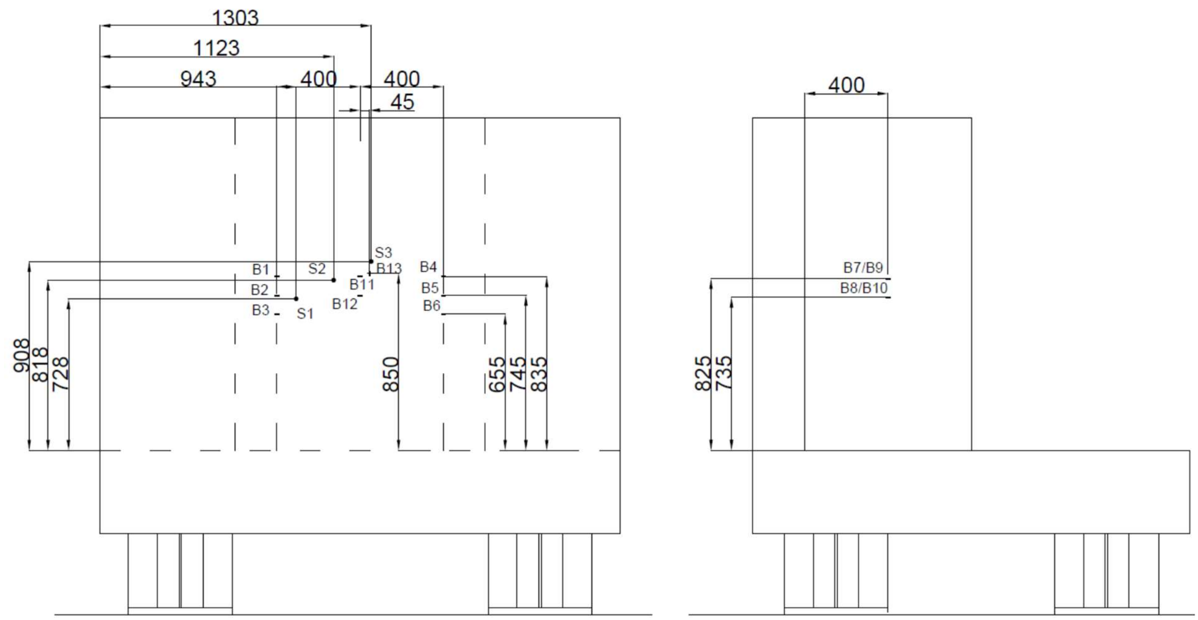

Figure 3. Locations of the strain gauges on the reinforcement.

Projectile

The projectile used in the test was originally designed for X-test series within Impact III project (Darraba et al., 2022). The design objective was to create suitable combination of "soft" loading due to mass flow and "hard" loading due to crushing strength to inflict both bending and punching type of damage on the target slab. This was achieved by proper selection of the diameter and the wall thickness of the projectile. The projectile is constructed by welding and the material of all parts is EN 1.4432 / AISI 316L. The narrow band at the front is used to strengthen the weld seam between the dome and the pipe of the projectile in order to prevent splitting failure of the pipe and to ensure proper folding. The projectile is shown in Figure 4 and nominal numerical information is compiled in Table 3. The parameters in the table are the outer diameter, Do, wall thickness, t, length, L, and mass, m.

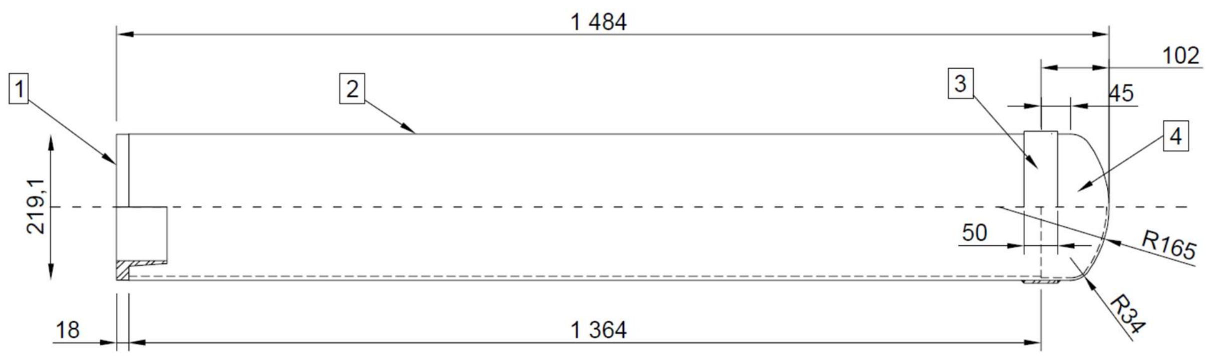

Figure 4. The projectile used in test NEX.

Table 3: Main dimensions of the projectile and its parts.

Part no.	Description	Do [mm]	t [mm]	L [mm]	m [kg]
1	Weldring neck				4.6
2	Pipe	219.1	6.35	1364	42.28
3	Band		4.0	50	1.12
4	Dome	219.1	3.76	102	3.02
Sum				1484	51.06

RESULTS

The realized impact velocity was 165.8 m/s. Based on the high-speed video material, the impact duration was 6.2 ms. Still pictures from the high-speed video material, taken 0, 2, 4 and 6 ms after the beginning of the impact, are shown in Figure 5.

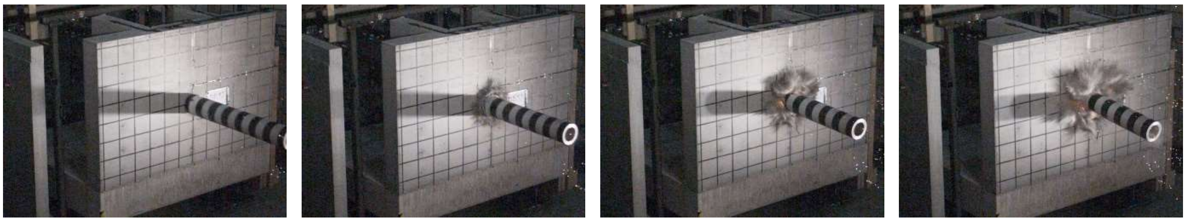

Figure 5. Snapshots of the impact at 0, 2, 4 and 6 ms.

The sawn horizontal cross-section of the impacted wall at the impact height is shown in Figure 6. As can be seen, the impact resulted in a clear shear cone that was detached from the surrounding concrete and pushed slightly backwards. Similar photographs from comparison tests X3 (v_0=142.7 m/s, $f_{c,cyl}$=46.6MPa, f_{ct}=3.09 MPa), X4 (v_0=168.6 m/s, $f_{c,cyl}$=41.8MPa, f_{ct}=2.26), X6 (v_0=166.7 m/s, $f_{c,cyl}$=55.8 MPa, f_{ct}=3.02 MPa) and X8 (v_0=166.7 m/s, $f_{c,cyl}$=58.4 MPa, f_{ct}=3.49 MPa) are shown in Figure 7. The comparison tests were carried out with 2.0×2.0 m 2-way simply supported slabs of the same thickness, bending reinforcement ratio and projectile type as the NEX test. The shear reinforcement ratio in tests X3 and X4 was the same as in test NEX while in tests X6 and X8 it was 1.8 times the value of test NEX. Perforation of the target was achieved in test X4 with the residual velocity of 25 m/s. In the other comparison tests, there were still intact concrete left to resist perforation, although not much. Clearly, the damage in test NEX is somewhere between these two cases.

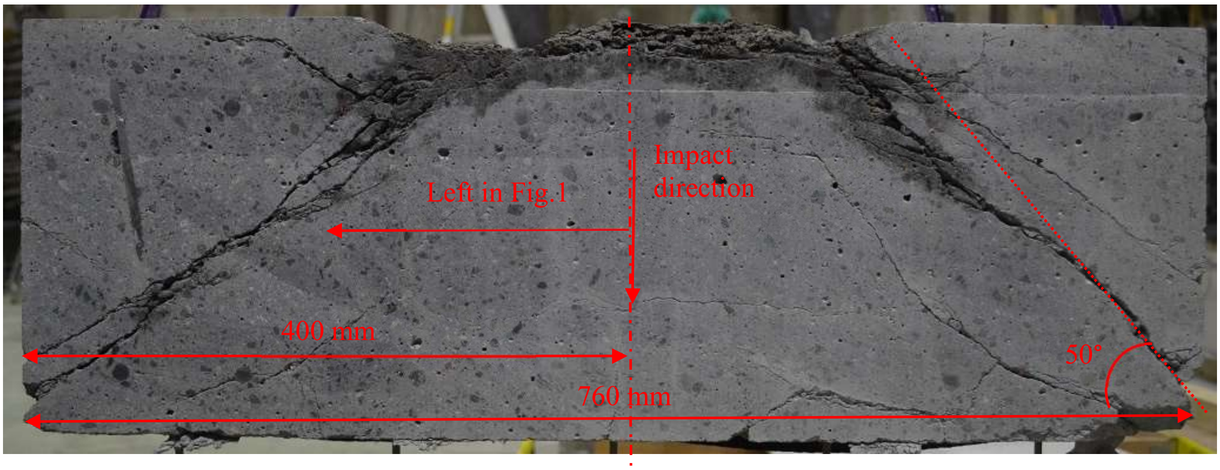

Figure 6. Horizontal cross-section of the impacted wall at the impact height.

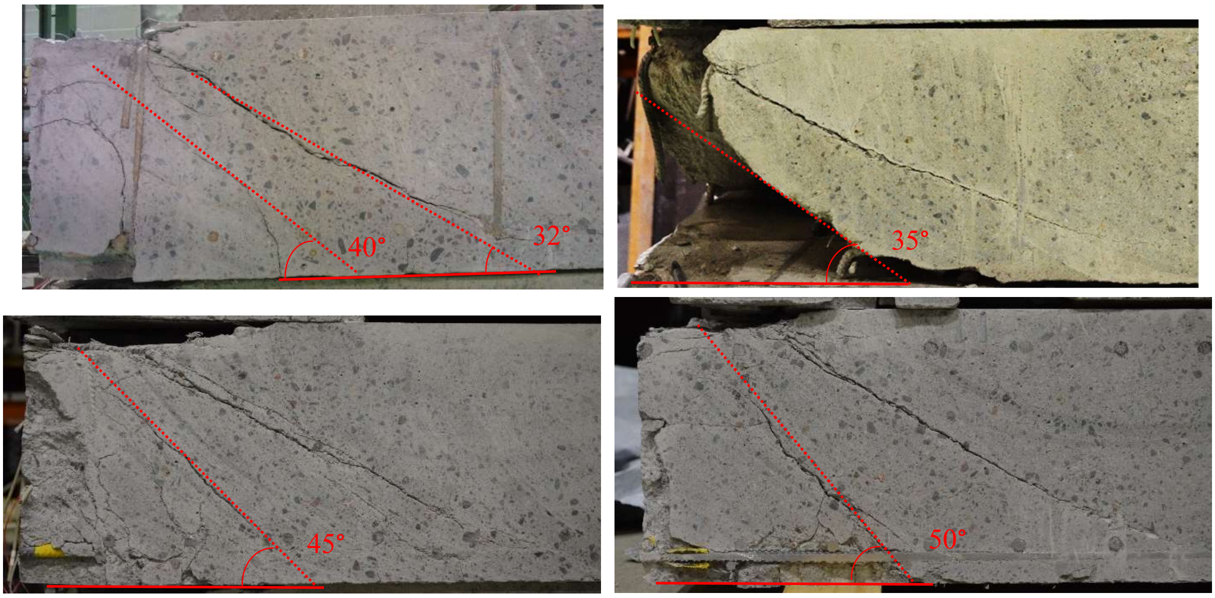

Figure 7. Horizontal cross-sections of comparison test slabs X3 (top left), X4 (top right), X6 (bottom left) and X8 (bottom right).

The rear surface of the impacted wall is shown in Figure 8. As can be seen, the impact caused a pronounced crack pattern. Similar cracking pattern was observed also in tests X3, X6 and X8. The outer diameter of the projectile, D_o, is marked in the photograph on the right as well as the approximate shear cone diameter, D_{SC}, of 760 mm.

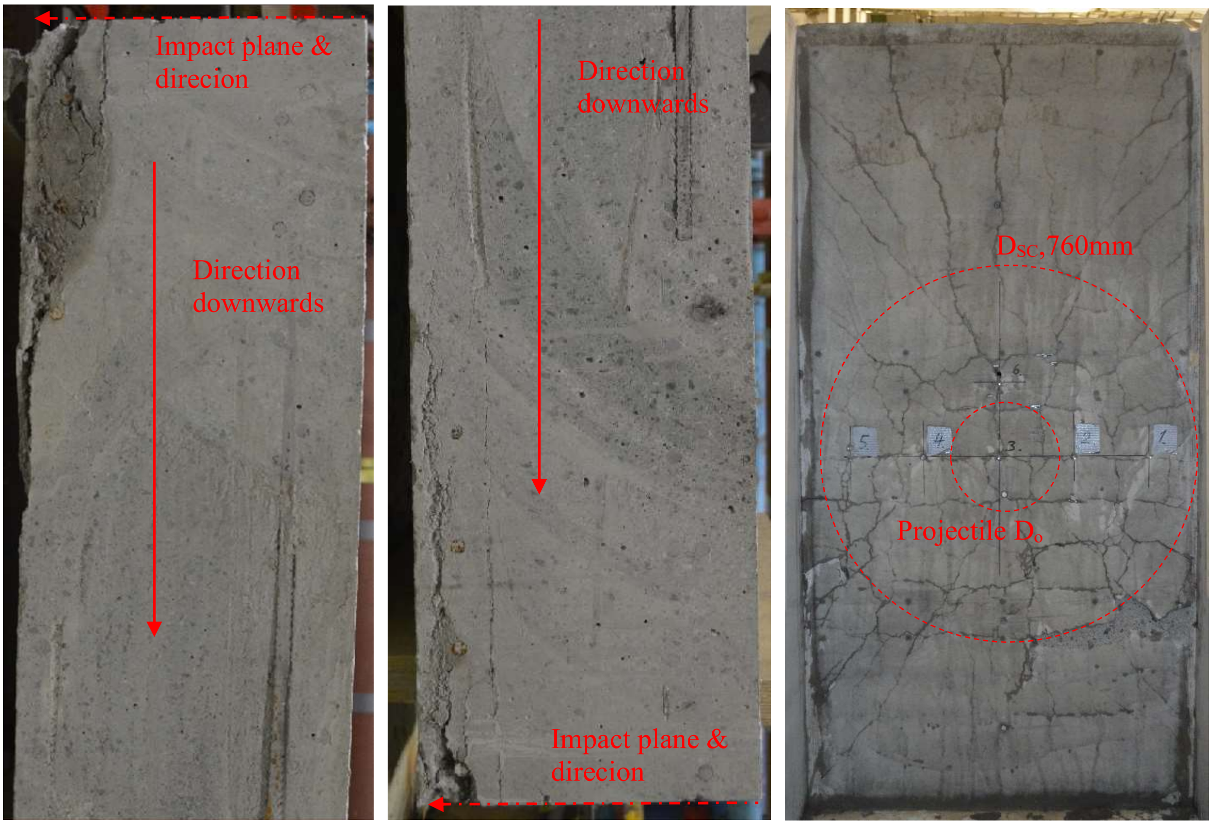

Figure 8. Left: Bottom half of the left support wall. Centre: Upper half of the left support wall. Right: Rear surface of the impacted wall.

The displacements measured at the impacted wall are presented in Figure 9 as a function of time. The maximum and permanent values are collected in Table 4. Relatively high permanent values indicate that close surroundings of the impact area are pushed back and detached from the surround concrete.

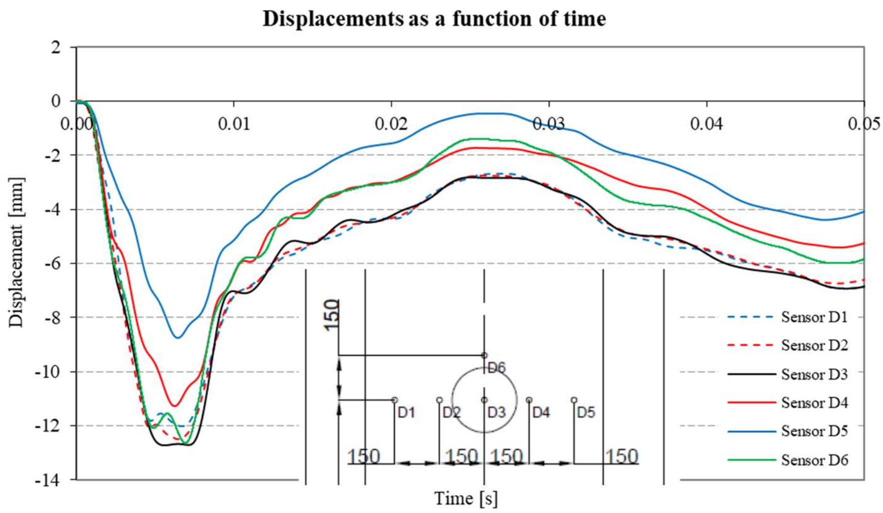

Figure 9. Displacements of the impacted wall as a function of time.

Table 4: Maximum and permanent displacements of the impacted wall.

Extreme and permanent values of displacements						
Sensor no.	D1	D2	D3	D4	D5	D6
Max. [mm]	-12.01	-12.50	-12.72	-11.27	-8.75	-12.64
at [ms]	6.70	6.47	5.60	6.23	6.44	6.91
Permanent value [mm]	-5.31	-5.27	-5.27	-3.97	-2.78	-4.17

The strains measured during the test at reinforcement bars are shown in Figure 10. The side walls act as moment bearing supports for the impacted wall. Therefore, the horizontal strains (B11) at the rear surface of the impact point are not as high as they would be with simple supporting. The strains measured with gauges B1 - B6 on the support area were all below 0.143 %. The only location with strain exceeding that of static yield was B11 The strains measured with the only functioning strain gauge on the shear reinforcement were likewise low. In tests X3 and X4, vast majority of the strains measured on the shear reinforcement were high (>4%). In tests X6 and X8, these strains were slightly lower but still all higher than the one obtained in test NEX. However, far reaching conclusions cannot be made on the basis of one measurement only.

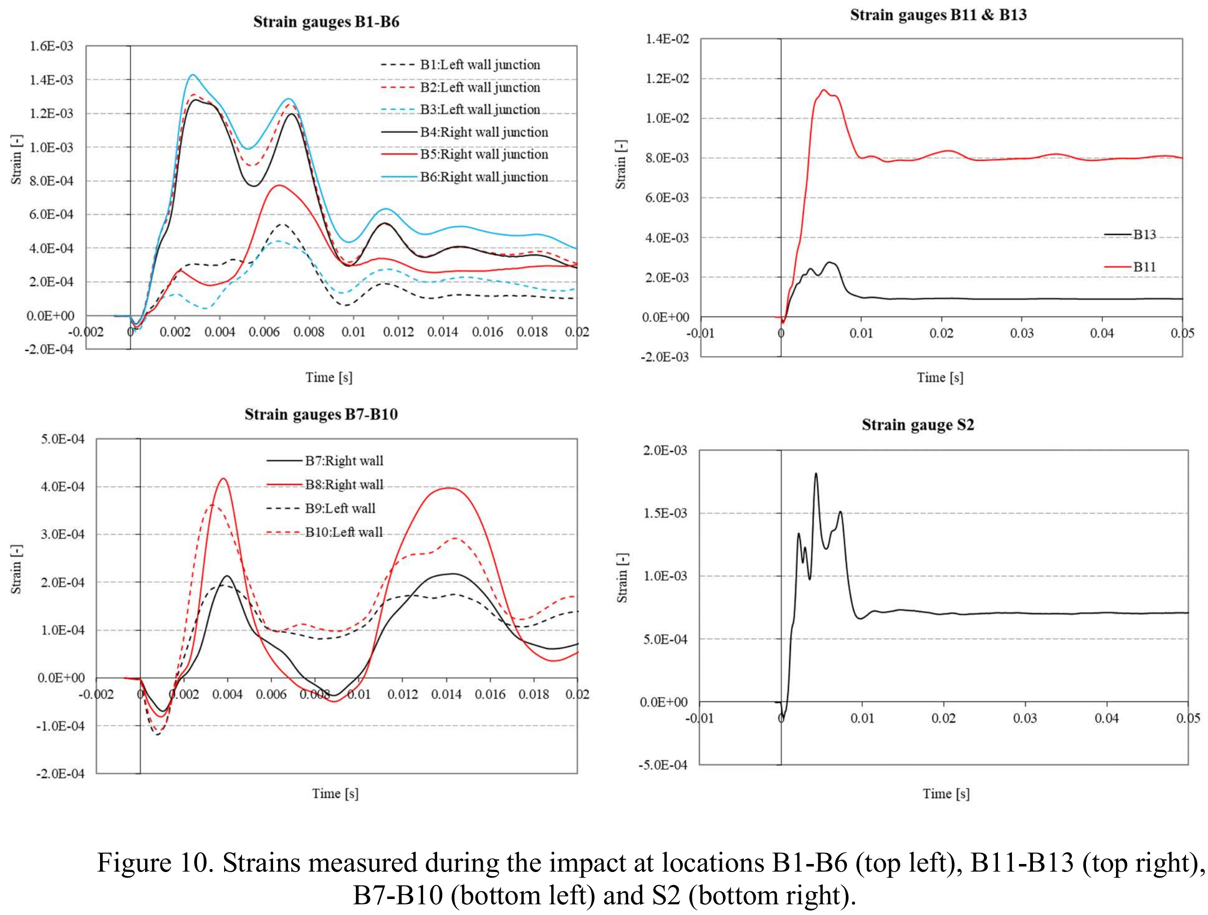

Figure 10. Strains measured during the impact at locations B1-B6 (top left), B11-B13 (top right), B7-B10 (bottom left) and S2 (bottom right).

The support forces measured during the impact at both horizontal as well as vertical supports are shown in Figure 11. The vertical support forces are further divided to front and rear supports. At first, the front and rear support forces are in opposite phases but soon start altering in the same phase. The graph on the right shows the impulse integrated from the horizontal support forces together with the momentum of projectile at the moment of the impact.

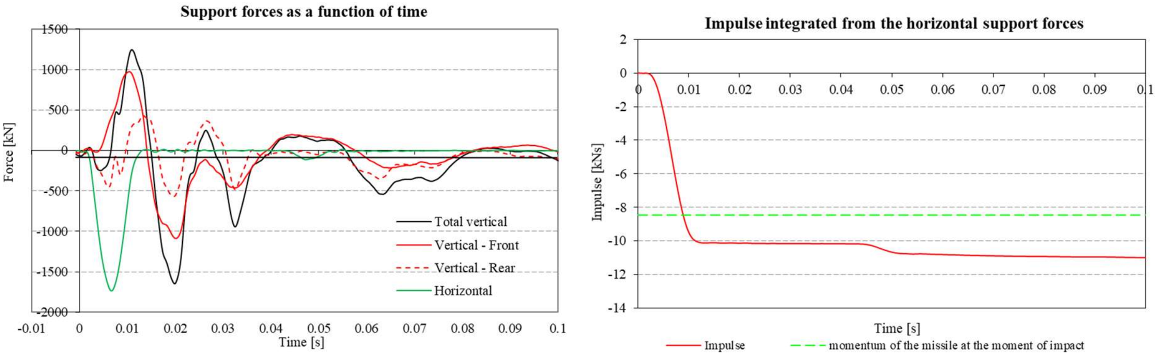

Figure 11. Left: Vertical and horizontal support forces as a function of time. Right: The impulse integrated from the horizontal support forces.

CONCLUSIONS

The effect of near support impact (one-way shear behavior) on increasing the shear capacity of reinforced concrete slabs subjected to impact loading is studied experimentally in this paper. The experimental damage is compared to reference tests in which the impact location is further from the support. The level of damage identified from the cross-sectional photographs refers to strengthening effect of the supporting walls behind the impacted wall.This is supported also by low level of strains measured with the only functioning strain gauge on the shear reinforcement. However, these strains seem to be relatively sensitive to the location of both the reinforcement bar in question as well as the gauge glued on it. The findings are consistent with shear force reduction at supports, enabled in Eurocode 2 (2005). However, additional experimental and numerical analyses is needed to validate the favouring effect of near support impact on increasing the shear capacity of reinforced concrete slab.

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