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IMPACT TESTING OF A WALL-FLOOR-WALL REINFORCED CONCRETE STRUCTURE

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ABSTRACT

Resistance of nuclear power plant (NPP) civil structures against a crash of a large airplane is generally verified with numerical models or semi-empirical and analytical formulas. In order to be reliable, used models and methods have to be validated against reliable empirical data, which is scarcely available in public. Vibration in an entire building induced by such a highly dynamic impact is one of the arising phenomena that need to be assessed in order to ensure the functionality of critical equipment and components of the plant.

In order to obtain experimental data for model validation, a series of three impact tests was carried out with a structure having a front wall, a floor and a rear wall, each being 150 mm thick. In addition to impact tests, the structure was subjected to modal testing before and after the first impact test and then after the last impact test. A soft projectile, resembling the fuselage of an aircraft and having mass of 50 kg, was used in the impact tests with the impact velocities ranging between 111.2 and 116.8 m/s. The response of the structure to the impacts was measured with accelerometers, displacement sensors and strain gauges on reinforcement bars. In addition to experimental data generation, the aim of the tests was to study how the vibration propagates from the hit point, how it gets damped and how these properties change when the structure is already damaged.

INTRODUCTION

Since 2006, VTT Technical Research Centre of Finland has carried out series of impact tests with reinforced concrete structures, funded and designed together with its domestic and foreign partners. The main purpose of the tests is to yield experimental results for validation of numerical modelling methods and semi-empirical or analytical formulas that can be used to assess the severity of an aircraft impact against reinforced concrete structures.

So far the tests that have been carried out have focused on bending behaviour of square walls under soft impacts (e.g. Tarallo et al., 2007), punching behaviour of square walls under hard impacts (e.g. Orbovic and Blahoianu , 2011), combined bending and shear damage under relatively soft impact (e.g. Borgerhoff et al., 2013) and the behaviour of liquid filled projectile (e.g. Sidle at al., 2011) and its effect on the bending behaviour of the target. The tests have been carried out by VTT with its test-bed, presented for example in the work by Lastunen et al. (2007).

One of the topics of interest that has not been studied so far is how vibration, induced by an impact of a soft projectile, propagates and gets damped in a reinforced concrete structure. This information would help to assess the magnitude of vibration that propagates from the impact point to the internal parts of the structure and that could be harmful for the components inside it. To obtain such data, a wall - floor - wall structure was built and tested three times with a soft impact on the front wall. The purpose was also to study whether pre-damage by previous tests affects the vibration propagation and dynamic properties of the structure. The structure was also subjected to modal testing to assess its dynamic properties before and after the impact tests.

TEST SET-UP

Geometry, Supporting and Materials

The tested structure had a front wall, a floor and a rear wall, each 150 mm thick. This type of structure resembles very coarsely a NPP reactor building with an outer wall and a base slab and with the rear wall in the place of internal structures. The front wall was pressed between two halves of a steel test frame, which were bolted together with 47 bolts with a diameter of 20 mm and estimated pre-tightening force of 135 kN in each bolt. The frame rested freely on wooden beams and was connected to solid bedrock with horizontal support pipes. At the back end of the floor slab, the structure rested freely on a 20 mm thick and 150 mm wide elastic bi-Trapez bearing ® manufactured by Calenberg Ingenieure. In addition, the front wall was suspended from the top of the frame with steel rods anchored to the wall. The structure and its supporting are shown in the drawings in Figure 1.

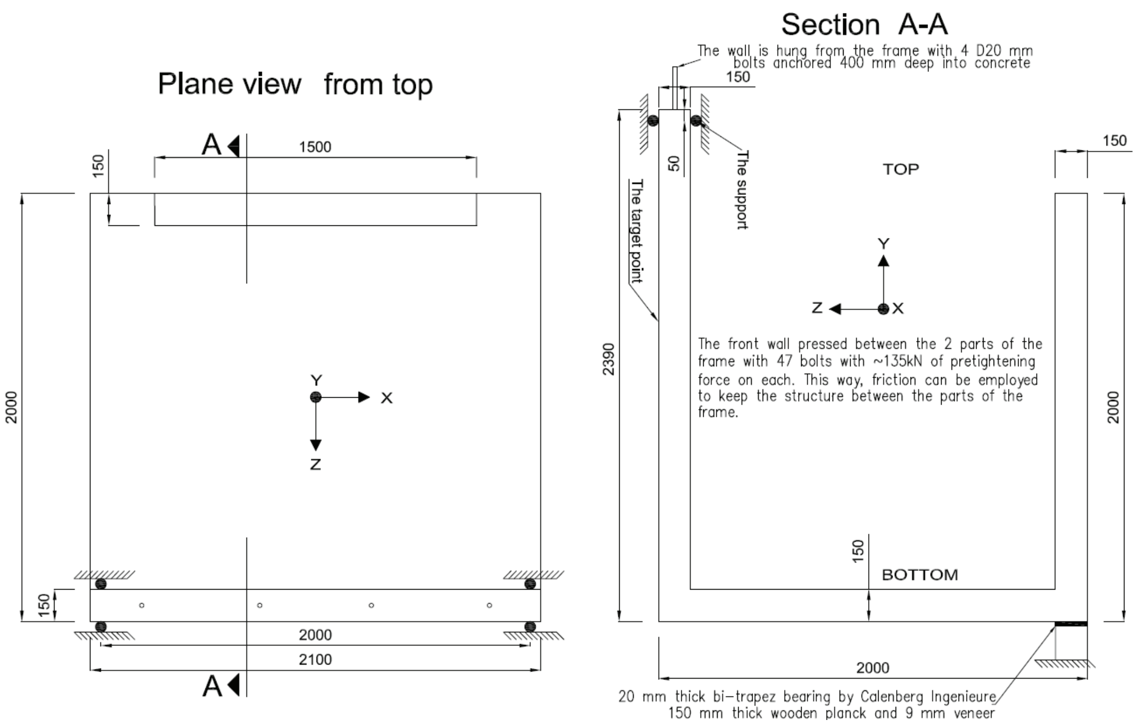

Figure 1. Left: The tested structure when viewed from top. Right: Section A-A of the structure.

Three similar tests were carried out with the structure. The projectile used in the tests was relatively soft and made out of stainless steel pipe with an inner diameter of 250 mm, a wall thickness of 2 mm and weight of 50 kg. The impact velocities in these tests, V0A, B and C, were 111.2, 113.6 and 116.8 m/s, respectively. The main purposes of the tests were to study how the vibration propagates from the hit point through the floor to the rear wall and how it gets damped in the process, study how this vibration behaviour changes when the impact is repeated against already damaged structure and yield reliable measurement data for validation of the numerical models made of the structure.

The front and the rear wall of the structure were reinforced with ϕ6 mm longitudinal bars with spacing of 50 mm in both faces and directions with the vertical (Y-axis) reinforcement being closer to the surface and concrete cover being 15 mm. The floor was reinforced with ϕ10 mm longitudinal bars with spacing of 50 mm in the horizontal direction (Z-axis) and with ϕ6 mm longitudinal bars with spacing of 50 mm in the transverse direction (X-axis) with the bars in horizontal direction being closer to the surface. Shear reinforcement was applied at 800 mm * 800 mm rectangular area around the hit point. The shear reinforcement type was a closed stirrup with a diameter of 6 mm and spacing of 200 mm in the transverse and 50 mm in the vertical direction.

The reinforcement bars of the floor were subjected to tensile tests resulting in yield strength, R_{eH}, ultimate strength, R_m, ultimate elongation, A_{10}, and total elongation under maximum load, A_{gt}. The results are shown in Table 1. The structure was cast in two pieces: first the floor and then the walls. The batches of concrete used were subjected to material tests resulting in unconfined compression strength, f_c, splitting tensile strength, f_{ct} and Young's modulus, E_c. The results are shown in Table 2.

Table 1: Tensile material test results for the reinforcement bars of the floor of the structure.

Bar diameter	Yield strength	Ultimate strength	Ultimate elongation	Total elongation under maximum load
d	R_{eH}	R_m	A_{10}	A_{gt}
[mm]	[MPa]	[MPa]	[%]	[%]
6	606.7	690.3	11.17	4.40
10	553.0	659.0	18.23	11.03

Table 2: Material test results of the concrete batches used to cast the floor and the walls of the structure.

Component	Compression strength		Splitting tensile strength	Young's modulus
	Cubic, $f_{c,c}$	Cylindrical, $f_{c,cy}$	f_{ct}	E_c
	[MPa]	[MPa]	[MPa]	[GPa]
Floor	56.0	54.5	3.44	25.447
Walls	52.8	46.8	2.75	27.078

Instrumentation and measurements

The quantities which were measured during the tests were: strains at 10 selected locations on the reinforcement, displacements at 7 degrees of freedom (DOF), accelerations at 6 DOF and horizontal support forces acting on the support pipes. The impact velocity was estimated using signals from two laser devices with beams running across the flying path of the projectile. The signals from the strain gauges were amplified with an in-house built amplifier. All the signals were measured with two industrial computers (Advantech 610 Industrial computer & National Instruments PXI -1000B) using National Instruments 4472 PXI/PCI dynamic signal acquisition modules, an in-house developed measurement code based on LabView platform and sampling rate of 102 kHz with the effective bandwidth being 45 kHz. Each impact was also documented with two high shutter speed video cameras, one located on the front side and the other on the backside of the structure, both taking 1000 frames per second. The locations and the measurement directions of the sensors are presented in Figure 2 for the displacement sensors (left) and accelerometers (right) and in Figure 3 (left) for the strain gauges on the reinforcement. A photograph of the structure is shown on the right in Figure 3 as ready to be tested.

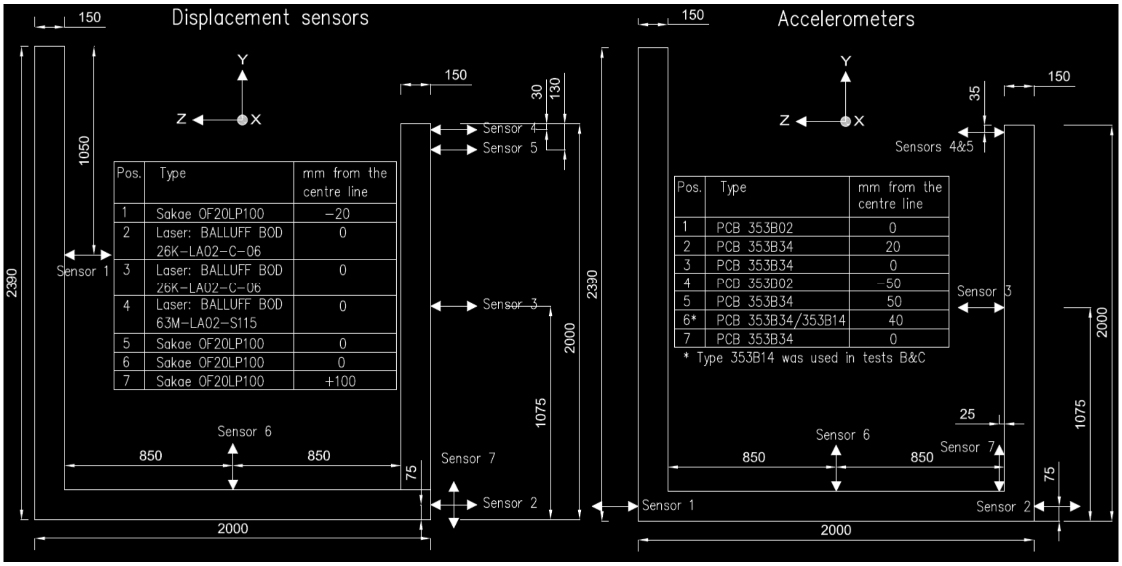

Figure 2. The type, location and measurement direction of the displacement sensors (left) and accelerometers (right) used in the tests.

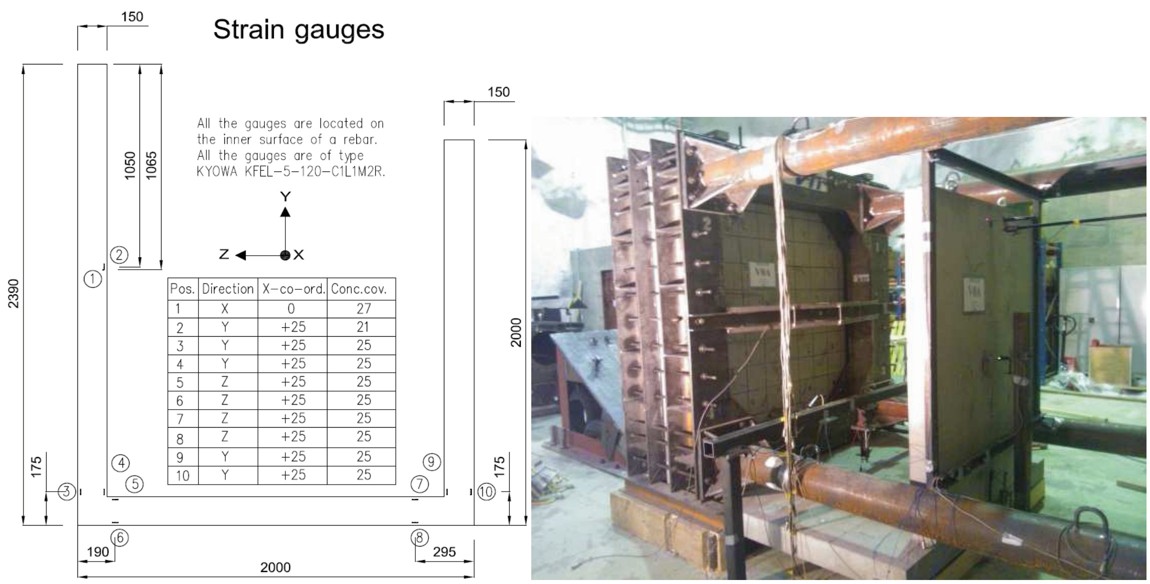

Figure 3. Left: The locations of the strain gauges on the reinforcement. Right: The structure as ready to be tested.

Modal Testing

In addition to impact tests, the structure was also subjected to modal testing. The goal of these tests was to determine vibration modes of the concrete structure used in the impact test as a target in-situ, i.e. when the structure is fixed into the test frame with the supporting pipes attached and how these modes change when the structure gest damaged. Three different test series discussed in the paper were carried out: first before the first impact test, then after the first impact test and finally after the last impact test.

Measurements for experimental modal analysis (EMA) were carried out using impact excitation as an input. This was given to the rear wall (MP101, the red dot on the rear wall in Figure 4) of the structure with an impact hammer (PCB, type 08642). The vibration response of the structure was measured with thirteen tri-axial accelerometers (Endevco E65-100). Signals were measured using 40-channel signal acquisition device (LMS, type Scadas SC310). Measurements and analyses were carried out using LMS TestLab-software (release 13A SL3). From the measurement method point of view, the useful bandwidth was approximately 1-350 Hz.

The measurement geometry of the structure, i.e. measuring points, is shown in Figure 4. Measuring points are marked with dots (MP 1-25, 31-60, 71-94, and 26-29, located on the front wall, the floor, the rear wall and the frame, respectively). The front wall is on the left (green dots and lines), rear wall on the right (yellow dots and lines). Coordinate arrows: green, blue, and red: correspond with X, Y, and Z axes, respectively. Z-axis is the vertical axis in this case (Y in the impact tests). The excitation point on the rear wall is marked with a red dot.

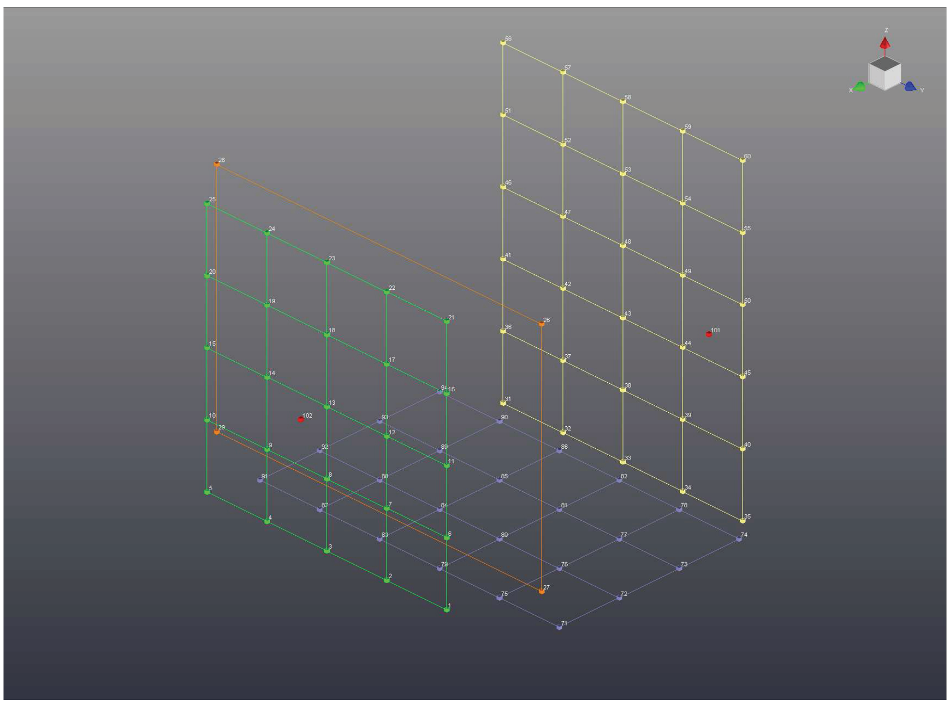

Figure 4. The measurement geometry of the structure for the modal tests.

TEST RESULTS

Damage Caused to the Structure

The damage that was caused to the structure by the impacts was quite mild and limited mainly to the proximity of the hit area on the front wall. The mild damage can be attributed to the intentionally low impact velocities and soft projectiles. The damage at the hit area on the front and the back surface after teach test C is shown on the left and in the middle of Figure 5. The photograph on the right shows cracks that appeared near the junction between the front wall and the floor where the contact surface between the frame and the front wall ended.

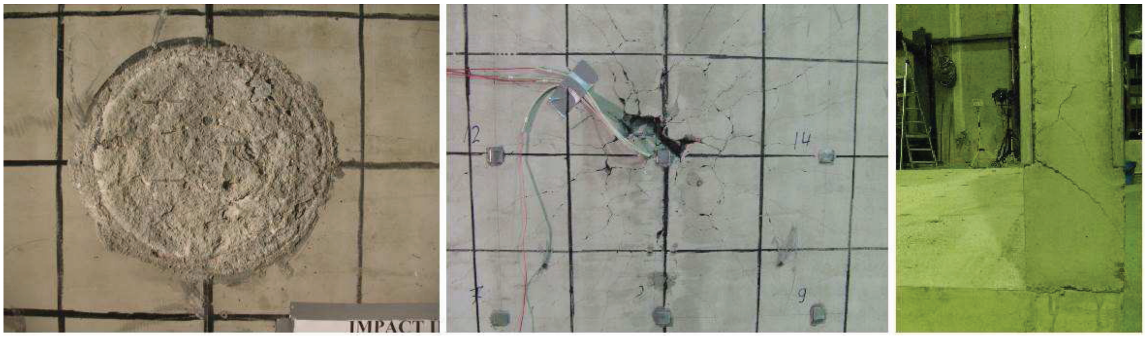

Figure 5. The front (left) and the backside (middle) of the front wall around the hit area after test C. Right: Cracks near the junction between the front wall and the floor after test C.

Modal Tests

Nine natural vibration modes were found in the modal tests which could be considered as the same for each measurement set. Modal Assurance Criterion (MAC) was used to verify that the identified shapes were really the same ones. Despite being the same modes, their frequencies and damping changed from one set to another. Figure 6 illustrates the first identified mode shape found at 16.0 Hz before the impact tests at its turning point. The natural frequencies of vibration of the 9 identified modes as well as the damping as percentage of the critical value are collected in Table 3 in case of each measurement set.

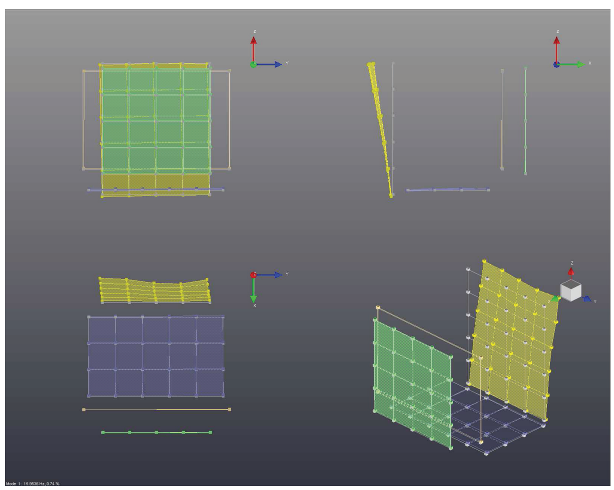

Figure 6. The first identified mode found at 16.0 Hz before the impact tests.

The natural frequencies decreased after each test with mode 2 making an exception. Mode 2 had a rise of 12 % in the frequency when the first and the last measurement sets are compared. Otherwise the frequencies decreased 5 – 28 % from the first measurement set to the last one with the average value being 10 % and the standard deviation being 11%. In a similar manner, in general, the damping values increased with modes 1 and 2 making exceptions as their damping decreased from measurement set 2 to 3. It is otherwise more difficult to draw a general rule for the change in damping than for the change in natural frequency as the variation in how the values change was big.

Table 3: The natural frequencies of vibration of the structure as well as the damping as percentage of the critical value measured before the tests, after the first test and after the third test.

Before the 1st impact test		After the 1st impact test		After the 3rd impact test	
Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
16.0	0.7	15.1	3.5	13.1	0.9
32.6	1.7	35.8	1.9	36.5	1.8
45.4	0.6	43.6	1.1	41.3	1.7
56.2	1.4	54.4	1.9	52.8	2.0
70.8	0.8	68.4	1.2	65.6	1.5
134.2	1.1	116.2	1.3	96.4	3.4
151.5	0.7	136.7	2.2	121.0	3.7
225.9	0.7	215.1	1.4	199.2	2.1
267.6	0.6	265.5	0.6	254.6	1.0

Accelerations

The highest peak accelerations were measured at the bottom of the front wall with sensor 1, nearest to the hit point. These peaks were roughly three times as high as the highest peaks measured in the horizontal direction at the midpoint of the rear wall (sensor 3). In general, the maximum range of acceleration (i.e. maximum peak - to - peak values), measured in different tests but at the same locations, decreased by 49 % on average from test A to test B and then by 19 % on average from test B to test C. The extreme values, defining the maximum range of values, were generally found at the very beginning of the impact with high frequency components dominating the response. While there were quite large differences in the maximum rage of values between the tests, the accelerations at the low frequency range were of the same order.

For most of the locations, one or two clear frequency peaks could be identified from the low-end frequency domain data. These peaks were slightly lower than the natural frequencies of vibration identified in the modal tests and roughly at the same frequencies than those identified from the strain and displacement measurement data and they decreased by 15 % on average from test A to test B and by 12 % from test B to test C. While comparing these frequency peaks to those obtained from the modal tests though, one has to remember that in the impact tests, the structure changes at the very beginning of the impact while during the modal tests this doesn't happen.

As an example of the accelerations, the ones measured with sensor 4 at the top of the rear wall in the horizontal direction in tests A-C are shown in Figure 7. Graph on the upper right shows only the duration of the actual impact, which was 19-20 ms, depending on the test, and estimated using the high shutter speed video footage. High frequency high amplitude accelerations were obtained at each measurement location and in each test during this actual impact. After this, these high frequency components died out quickly. The graphs on the bottom row show the frequency composition of these accelerations in a form of an auto power spectrum (APS) in the range 0 – 150 Hz, presented in a logarithmic scale. As can be seen, at the low-end frequency range, there aren't much differences between the tests. These could be found at high frequencies, where especially the results from test A are higher than those measured in tests B and C.

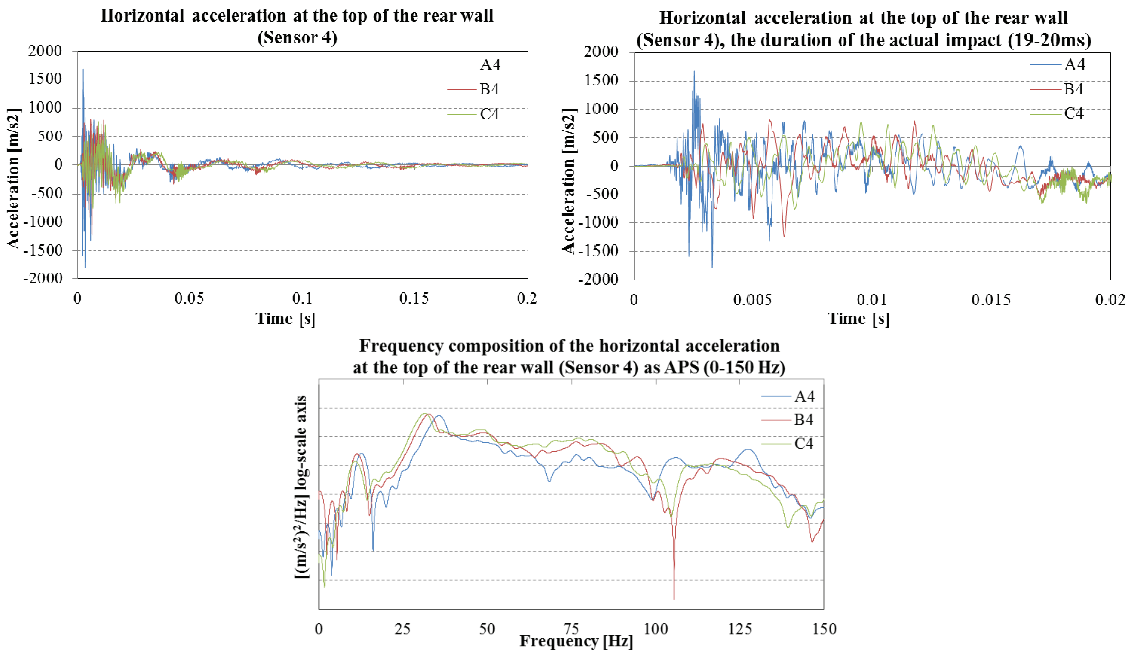

Figure 7. Top left: The horizontal accelerations measured at the top of the rear wall. Top right: The same data including only the duration of the actual impact. Bottom: The frequency composition of the accelerations measured at the top of the rear wall within range 0 - 150 Hz.

Displacements

The displacements were successfully measured at the floor as well as at the rear wall. Sensor 1 on the front wall worked well only in the first test and became de-attached afterwards. The values measured and presented here were “additional” ones meaning that any permanent values resulting from previous tests were set to zero when starting the new test.

The range of the measured displacements in the horizontal direction varied from 1.97 mm, measured in the middle of the rear wall in test A, to 9.08 mm, measured at the top of the rear wall in test C. In the vertical direction, the range of values varied from 2.95 mm, measured at the bottom of the rear wall in test A, to 5.97 mm, measured at the same location in test C. The range of values increased by 34 % on average from test A to test B and by 17 % from test B to test C. Especially the horizontal displacements took place clearly on two distinct frequencies, at 11-13 Hz and at 31-36 Hz which were roughly the same than those of the strain variation and acceleration. These frequencies decreased by 8-9 % from test A to test B and by 3-4 % from test B to test C

As an example of the displacements, the horizontal ones measured at the middle of the rear wall in tests A-C are shown in Figure 8. The graph on the left shows the displacements as a function of time while the graph on the right shows the corresponding frequency decomposition in a form of an APS, presented using logarithmic vertical axis.

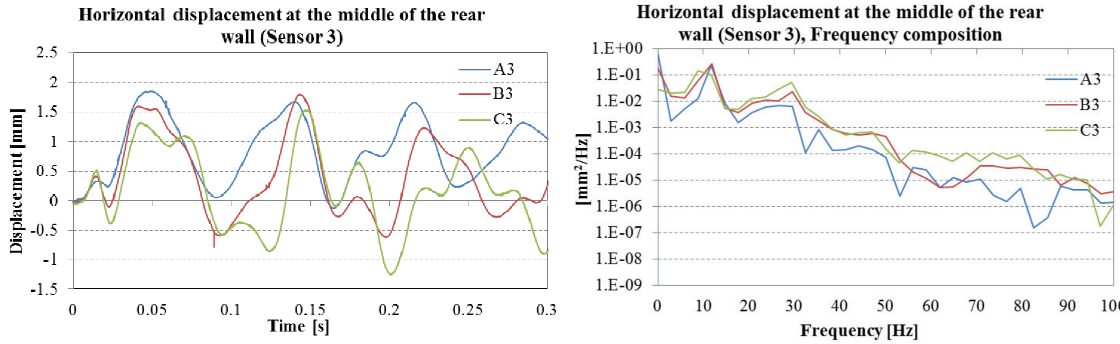

Figure 8. The time-history (left) and its frequency composition (right) of the horizontal displacements measured at the middle of the rear wall.

Strains on the Reinforcement

Only the strains measured at the hit area exceeded the static yield limit of the reinforcement bars. If we consider the permanent strain at the end of the previous test as the starting point of the measurements for the next test, the highest strain, 5.89 % , was measured in test B with strain gauge 2 located at the hit point on a vertical rebar near the back surface of the front wall. In test C, this gauge, or its wiring got broken. The strains at the junction between the front wall and the floor were roughly one decade lower and the strains at the junction between the floor and the rear wall two decades lower than those at the hit area. No clear tendency could be identified for the change of behaviour of the stresses between the consecutive tests. However, the additional permanent strains decreased from a test to the next. The elastic strain variation happened mainly at two frequencies which were slightly lower than the natural frequencies of vibration identified in the modal tests. These frequencies decreased by 6-9 % from a test to the next.

Figure 9 shows “additional” rebar strains at two locations. In this context word additional mean that they should be summed with the residual strains of the previous tests in order to yield the actual strain acting on the rebar. The graph on the left shows the strains measured with gauge 2 while the one on the right shows the strains measured near the front surface of the rear wall in a vertical rebar, near the junction between the wall and the floor. As can be seen, the ones at the hit location do not show remarkable post impact oscillatory behaviour due to high plastic strains. On the other hand, the strains on the rear wall stay within the elastic range and thus show clear vibration behaviour.

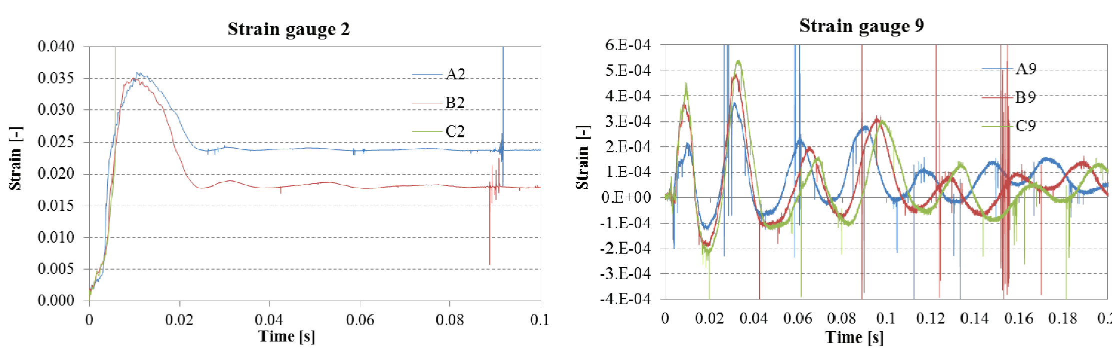

Figure 9. The strains measured on the vertical reinforcement at the hit location (left) and on the vertical reinforcement of the rear wall near the junction to the floor (right).

SUMMARY AND CONCLUSIONS

In order to study vibration behaviour in reinforced concrete structure, a three-dimensional reinforced concrete test specimen with a front wall, a floor and a rear wall, each 150 mm thick, was impacted three times with a deformable steel projectile. Modal tests and analyses were also carried out for the structure before and after the first impact test as well as after the last impact test. In the impact tests, the response of the structure was measured with strain gauges on the reinforcement, displacement sensors and accelerometers. The main aims of these tests were to yield reliable experimental data for validation of predictive methods, to study propagation of vibrations from the hit point through the floor to the rear wall and to study how the dynamic properties and the response of the structure changes as it gets more and more damaged.

In summary, the damage caused for the structure by the tests was relatively mild and limited to the front wall where spalling of concrete took place at the hit area on the front surface and cracking as well as minor scabbing at the back surface just opposite to the hit area. In addition, cracks could be observed also at the sides of the front wall near the location where the wall changes to the floor. The minority of the damage was mainly due to soft impacts with low velocities.

The change in response of the structure between the consecutive impacts depended on the type of quantity measured: the displacements increased somewhat from a test to the next one while the accelerations decreased in a similar manner. At the same time no clear behaviour could be identified for the reinforcement strains. In each case, the main frequencies at which the response occurred decreased slightly from a test to the next one with the frequencies being slightly lower than the ones identified in the modal analyses.

All in all, the test series was a successful start for testing of vibration propagation and damping properties of three-dimensional reinforced concrete structures under soft projectile impact. It gave a wealth of valuable data for validation of predictive models. It also gave valuable experience that can be used in future when designing similar tests.

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