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INDUCED VIBRATIONS OF A REINFORCED CONCRETE STRUCTURE TESTED IN IRIS PHASE 3 PROJECT SUBJECTED TO IMPACT BY A DEFORMABLE MISSILE

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ABSTRACT

Phase 3 of the IRIS project ("Improving Robustness Assessment of Structures Impacted by a Large Missile at Medium Velocity") is organized by the OECD and is a follow-up project of the preceding phases IRIS_2010 and IRIS_2012. IRIS Phase 3 is dedicated to the transmission of the induced vibrations proceeding from the impacted wall of a reinforced concrete building to floors and walls outside the impact zone. Besides three other institutions, ENSI is contributing to IRIS Phase 3.

The aims of this benchmark project are to evaluate the effects of the local damage due to impact on the induced vibrations, to measure the structural damping in the areas with linear-elastic behaviour as well as in the damaged areas, to draw conclusions regarding the most important influencing parameters from the obtained data base, as well as to refine and validate the computational methods – here in terms of vibration transmission and response spectra.

The box-shaped test specimen with open sides consists of front and rear wall as well as floor and ceiling slab. The projectile is to impact on the front wall. The rear wall is extended by an attic at the top. The test specimen is supported by four anchored feet consisting of pipe profiles. On the inside of the rear wall, two construction elements for the simulation of equipment components are mounted, which are fastened at the anchor plates by welded resp. bolted connections.

Nonlinear dynamic analyses of displacements, strains, support forces and accelerations are carried out by use of a SOFiSTiK model with layered shell elements. The results are compared to the measurement data and assessed involving the experience gained from the IMPACT project carried out by VTT in Finland.

INTRODUCTION

The Nuclear Energy Agency (NEA) of the OECD (Organization for Economic Co-operation and Development) launched the activities for phase 3 of the IRIS project ("Improving Robustness Assessment of Structures Impacted by a Large Missile at Medium Velocity") in August 2016, see Hervé (2016). The objective of the preceding two phases IRIS 2010 was to predict the nonlinear, dynamic behaviour of the missile and the reinforced concrete (r/c) target for three separate impact scenarios. The 3rd phase of the IRIS program dedicated to the transmission of the induced vibrations from the impacted wall to walls outside the impacted area was divided into several activities.

At first, participants were asked to calibrate their computer model by carrying out post-calculations of one of the vibration tests, which were performed in the frame of the IMPACT III project. The authors have reported about their numerical investigations on the vibration propagation and damping tests of IMPACT III at the last SMiRT conference, see Borgerhoff et al. (2015).

Subsequently, blind calculations of three consecutive impact tests on a mock-up newly developed for the IRIS Phase 3 benchmark should be carried out. The new tests were funded by the institutions ENSI, EDF, IRSN, and STUK. The box-shaped test specimen with open sides consists of front and rear wall as well as floor and ceiling slab. The projectile is to impact on the front wall. The rear wall is extended by an attic at the top. The test specimen is supported by four anchored pedestals consisting of pipe profiles. On the inside of the rear wall, two construction elements for the simulation of equipment components are mounted, which are fastened at the anchor plates by welded resp. bolted connections.

The IRIS Phase 3 impact tests were realised in October 2016. In this paper, a representative selection of results of the blind nonlinear dynamic analyses performed by the authors is compared to the data of the test results, which have been transferred to the benchmark participants meanwhile. In the current last part of IRIS Phase 3, a calibration of the numerical simulation models shall be conducted.

DESCRIPTION OF THE TESTS

The overall testing environment installed for the impact tests at VTT laboratories in Espoo (Finland) is shown in Figure 1. The projectile is ejected by means of a gas tube in direction of the target.

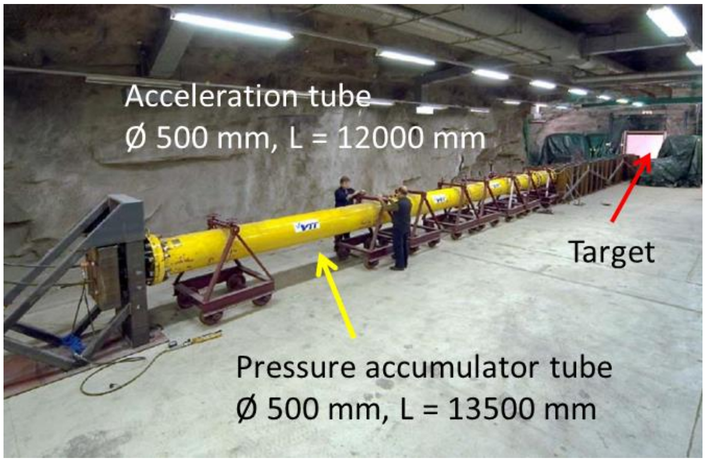


Figure 1. VTT testing environment.

The outer dimensions of the box-shaped r/c mock-up, which is depicted schematically in Figure 2, are 2.5 m width, 2.0 m height (front wall), 3.0 m height (rear wall) and 2.1 m depth. Except the floor thickness of 0.4 m, the structure parts have a wall thickness of 0.15 m. The mock-up is supported by means of four steel pedestals, which are designed for transmission of vertical as well as horizontal forces to the anchorage in the floor of the test hall by Dywidag rock anchors with a diameter of 32 mm and material of St 950/1050. The pseudo-equipments of steel are mounted on the inside of the rear wall by plates with embedded anchors. The finished mock-up structure and the pseudo-equipments at the rear wall according to Vepsä et al. (2016) are shown in Figure 3.

The concrete quality used for the mock-up is C40/50 with the maximum aggregate size being 8 mm. The basic reinforcement of walls and ceiling consists of steel bars B500B with diameter 6 mm and spacing 50 mm. The front wall is completely shear reinforced with diameter 6 mm hooked stirrups and spacing 100 mm/50 mm.

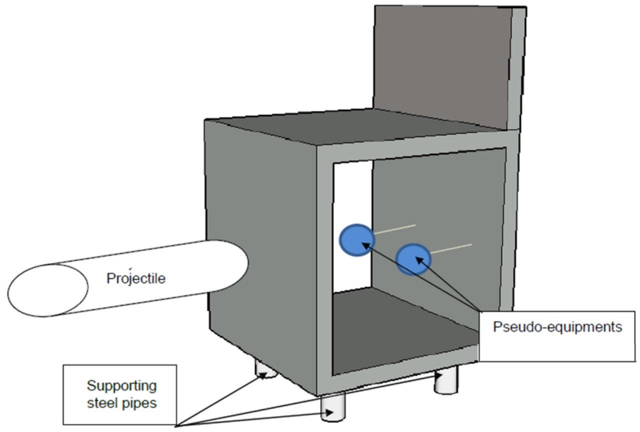


Figure 2. Schematic illustration of the impact test.

Figure 3. Mock-up structure (left), pseudo-equipments as installed at the rear wall (right).

The IRIS Phase 3 test series comprises three consecutive impact tests. Two types of deformable projectiles were used. The projectile for tests 1 and 2 with a pipe length of 1500 mm is shown in Figure 4. Instead, the pipe length of the projectile for test 3 is 2400 mm. The total mass of both types of projectiles is about 50 kg. The planned impact velocities were 90 m/s for tests 1 and 2 with the aim of limiting the system response to mainly reversible deformations, and 170 m/s for test 3 striving for significant nonlinearities particularly in the impact zone.

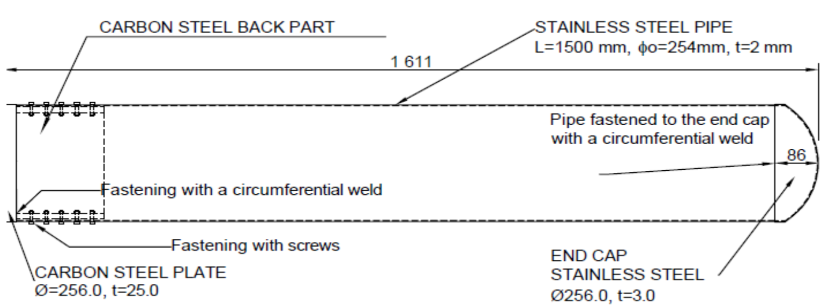


Figure 4. Projectile used in tests 1 and 2.

FE MODEL AND ANALYSIS

The nonlinear dynamic computations of the mock-up have been performed under the simplified but sufficiently precise assumption that the behaviour of the deformable missile is decoupled from the behaviour of the impacted r/c structure. In this case the effect of the missile is represented by the load function resulting from a numerical analysis of the impact on a rigid plane target. For this purpose, the two types of projectiles have been modelled as Finite Element (FE) models by use of 12734 elements (1/4 of the structure, 4-nodes doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains), see Figure 5. The computations with Abaqus, SIMULIA (2013), thankfully were carried out by Principia Ingenieros Consultores S.A. on behalf of the authors.

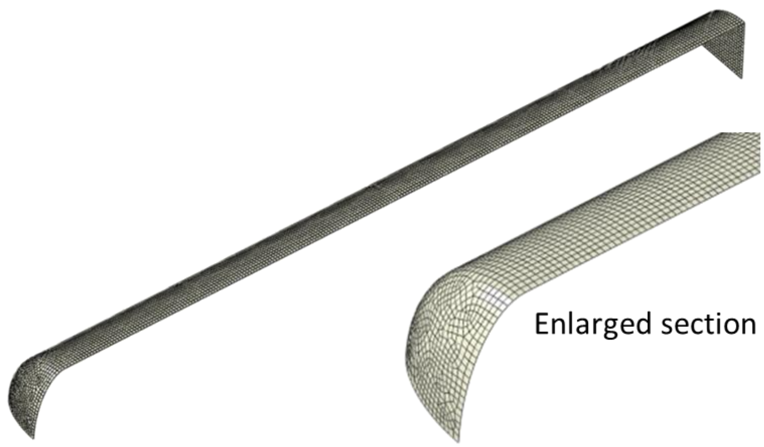


Figure 5. Abaqus FE model of the missile.

The deformed structures, computed under the assumption that the projectile acts with impact velocities of 90 m/s (first two tests) and 170 m/s (third test) on a rigid plane target, are shown in Figure 6. For tests 1 and 2 in the final deformation state, the length L_T of the non-crushed part of the missile was 0.72 m, and the length of the crushed part H_T was 0.17 m (measured values in tests 1 and 2 0.16 m and 0.15 m resp.). In test 3 the length L_T of the non-crushed part of the missile was 0.44 m, and the length of the crushed part H_T was 0.36 m (test result 0.33 m). The good agreement between the results of the numerical simulations and the geometry of the crushed projectiles allows the conclusion on a comparably good quality of the load functions. The time histories of the contact forces between missile and target, which define the load functions for the calculations of the mock-up, are depicted in Figure 7.

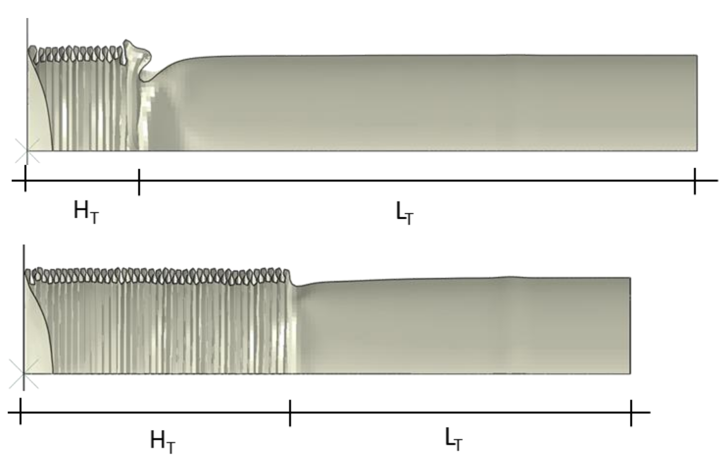
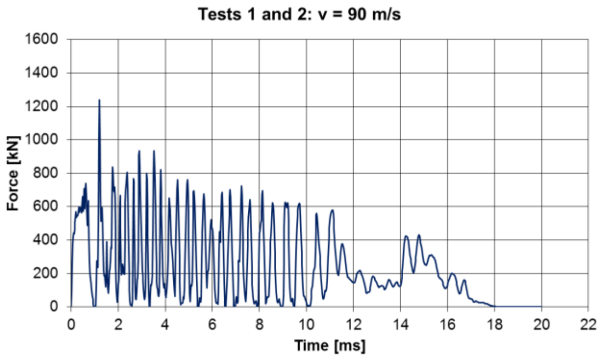


Figure 6. Deformed projectile test 1 and 2 (above), deformed projectile test 3 (below).



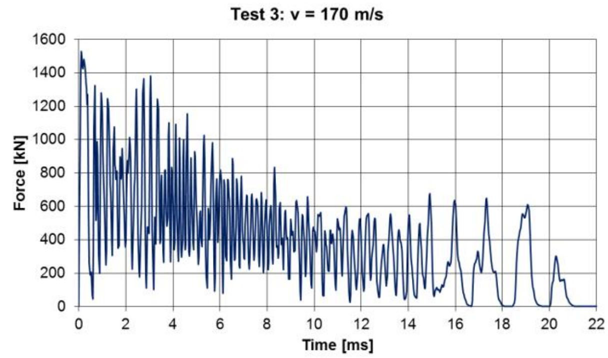
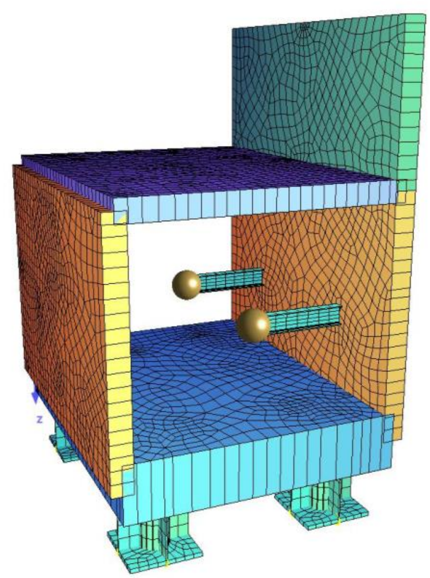


Figure 7. Load-function test 1 and 2 (left), load function test 3 (right).

The dynamic analyses were carried out by a FE model of the mock-up structure using the program code SOFiSTiK (2012/2014), see Figure 8. The r/c structure of the test specimen is modelled with non-linear, layered shell elements subdividing the slabs and walls into 12 layers and regarding the crosswise reinforcement at both sides. Damping of concrete was introduced by Rayleigh parameters adjusted to 1 % of critical damping for the relevant frequency range of eigenfrequencies between 30 Hz and 80 Hz. This assumption applied to the whole concrete structure leads to a damping value of 4.5 % at 500 Hz. The decisive time increment used in the analysis is 0.05 ms, hence a frequency range of 4 kHz is captured. The first eigenfrequency of the mock-up at the start of the tests (uncracked concrete) is shown in Figure 8 (right).



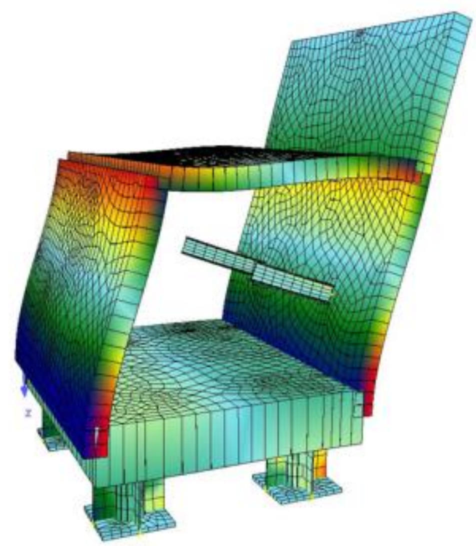


Figure 8. FE model of IRIS Phase 3 mock-up (left), 1. Eigenmode with frequency 17.9 Hz (right).

COMPARISON OF MEASURED AND COMPUTED RESULTS

The three impact tests of IRIS Phase 3 were carried out in November 2016. The velocities obtained in tests 1 and 2 were 91.8 m/s and 93.5 m/s resp. instead of the planned 90 m/s. The realised velocity of test 3 was 167 m/s (planned 170 m/s). The installed monitoring system comprises displacement, strain and acceleration sensors as well as sensors for measuring of the reaction forces. Based on the computed and measured acceleration data moreover response spectra were derived.

Figure 9 illustrates the locations of displacement data measurements. The subsequent diagrams show comparisons of computed and measured horizontal displacement time histories at three selected locations, namely the measuring point at the left side of the front wall (D02) in Figure 10, at the top of the attic (D7) in Figure 11, and at the rear wall (D9) in Figure 12.

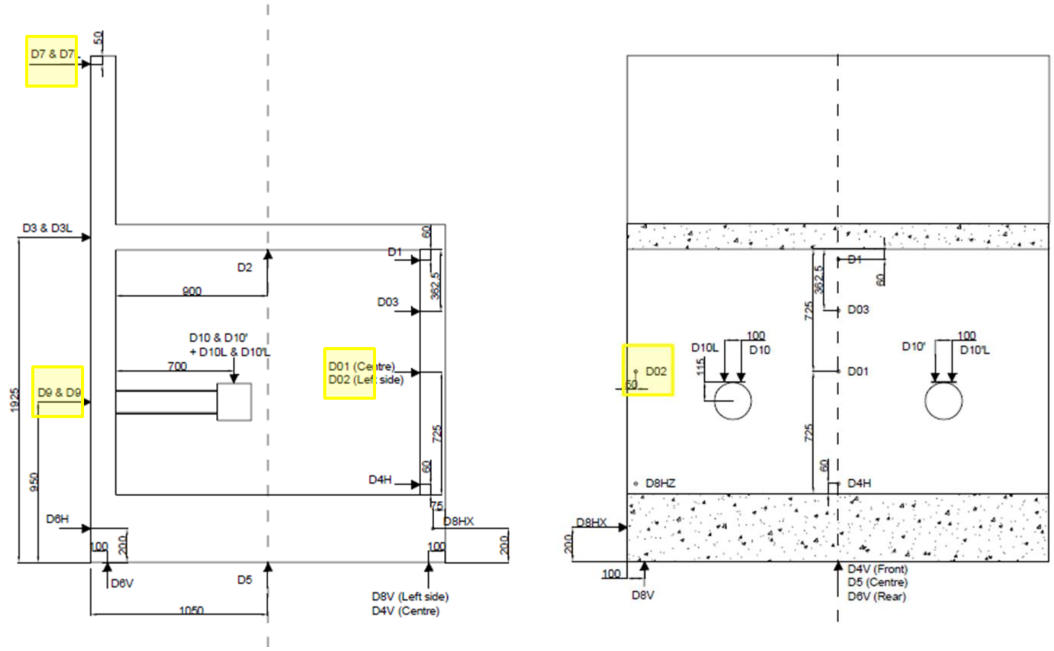


Figure 9. Location of displacement sensors, side view (left), front wall and equipments (right).

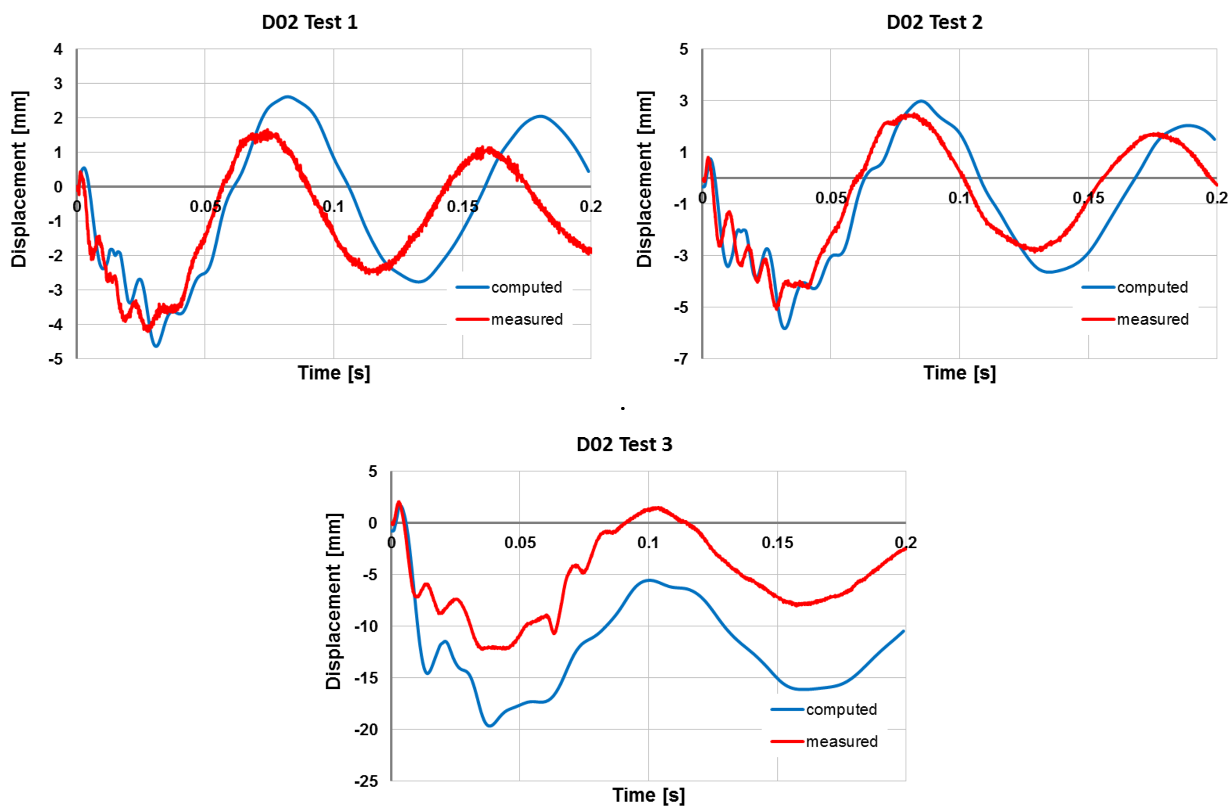


Figure 10. Horizontal displacements at location D02; tests 1, 2 and 3.

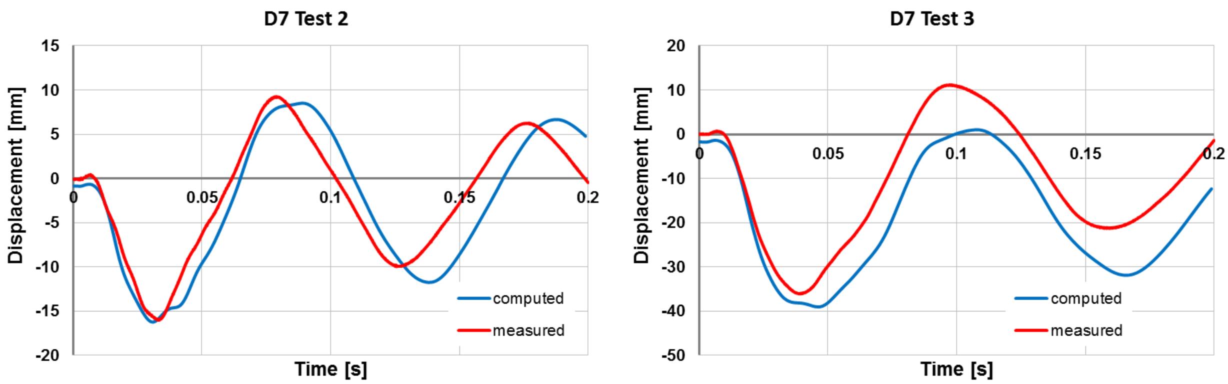


Figure 11. Horizontal displacements at location D7; tests 2 and 3.

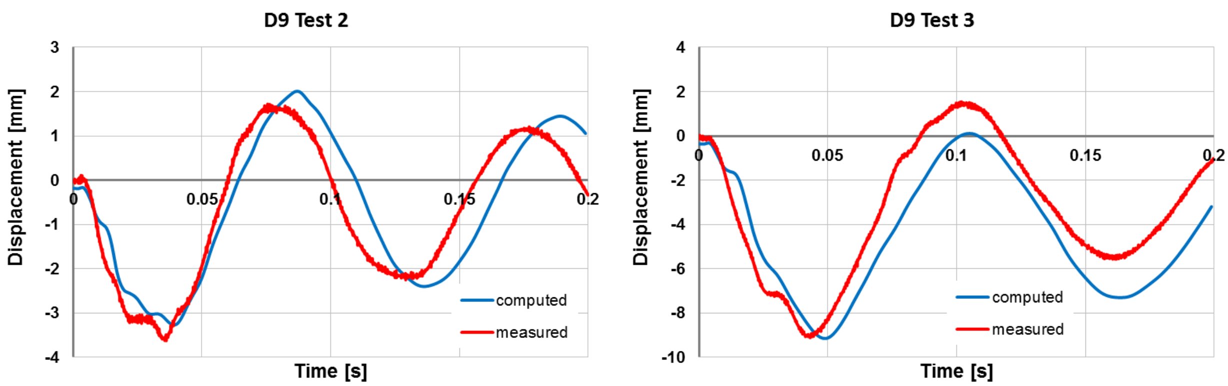


Figure 12. Horizontal displacements at location D9; tests 2 and 3.

Figure 13 shows the locations of acceleration sensors. The spatial arrangement is similar to the displacement sensors. Figures 14 to 16 depict horizontal accelerations at three locations for tests 2 and 3.

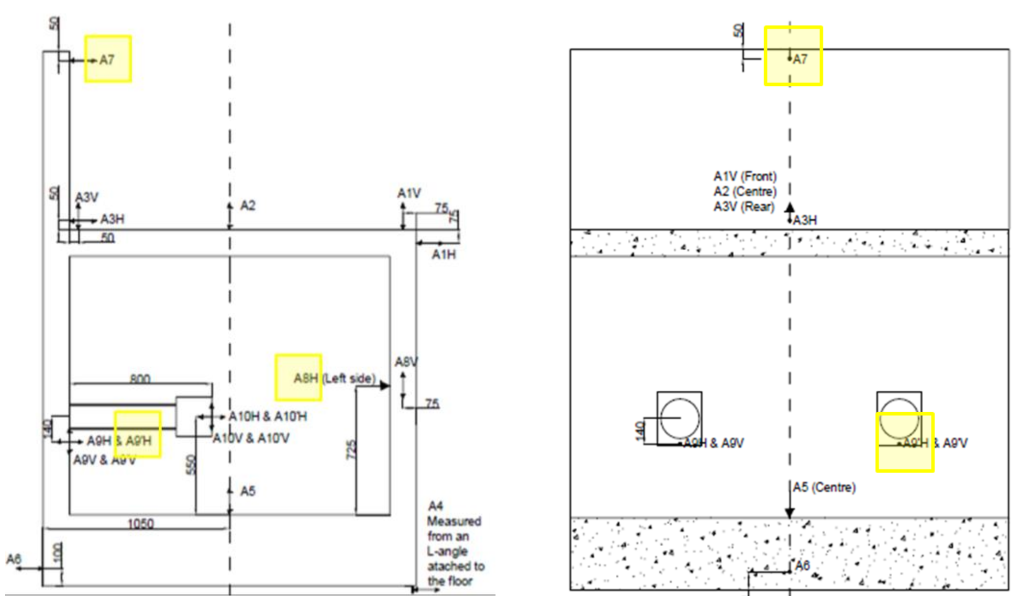


Figure 13. Locations of acceleration sensors, side view (left), rear wall (right).

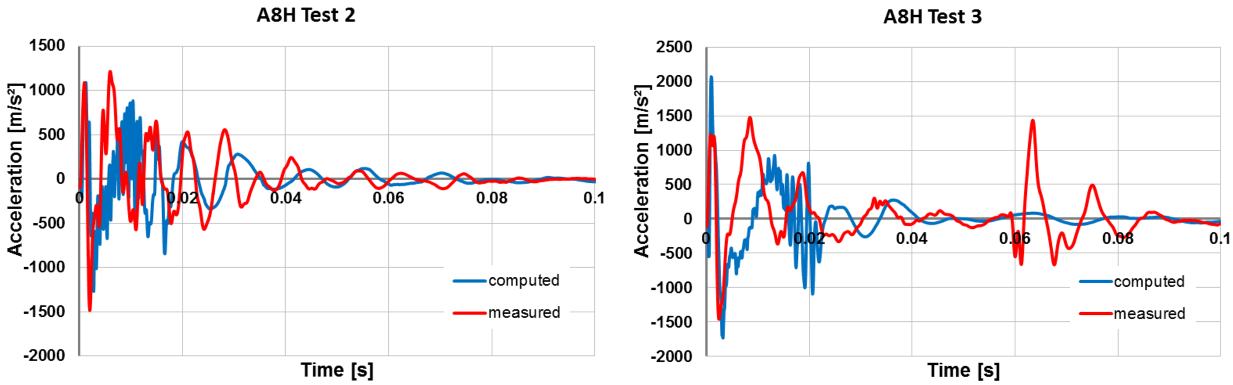


Figure 14. Horizontal accelerations at location A8H; tests 2 and 3.

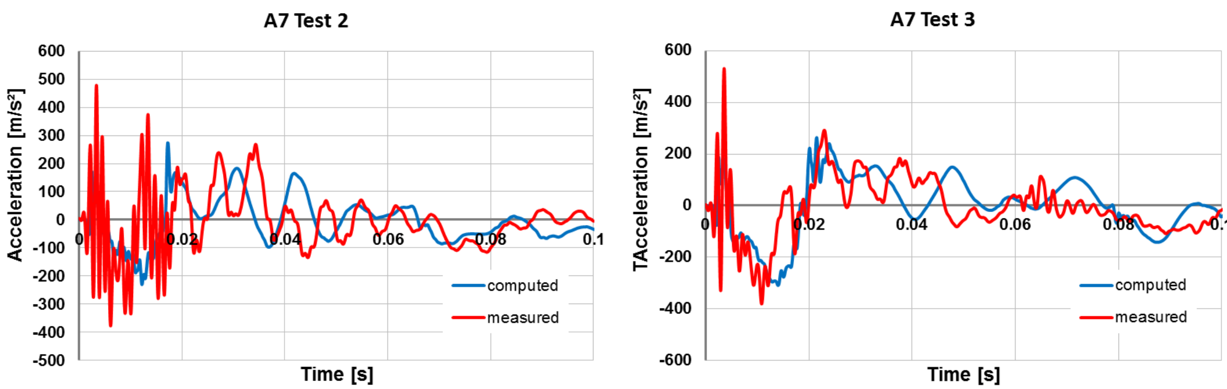


Figure 15. Horizontal accelerations at location A7; tests 2 and 3.

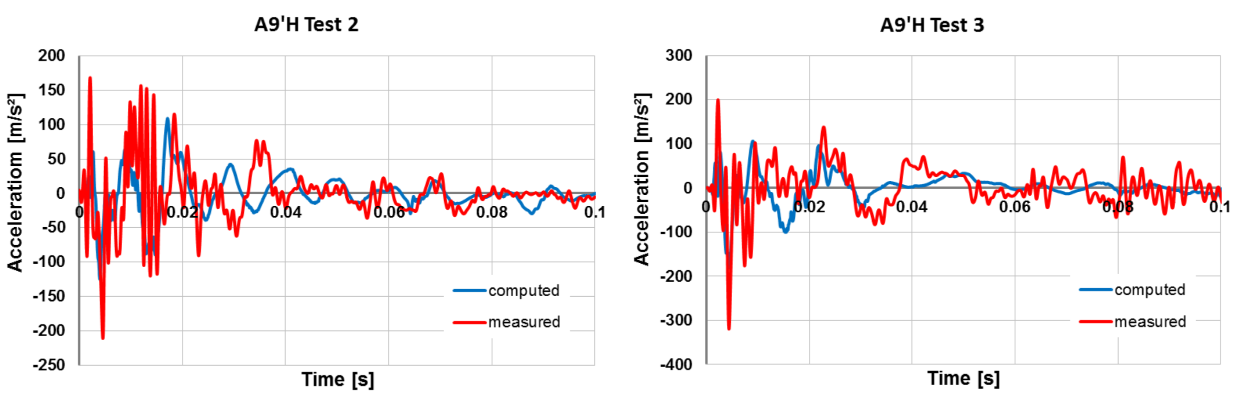


Figure 16. Horizontal accelerations at location A9’H; tests 2 and 3.

In the measured acceleration histories the fraction above 1 kHz has been filtered. Associated acceleration and displacement response spectra comparing measured and computed results of the three tests are shown in Figure 17.

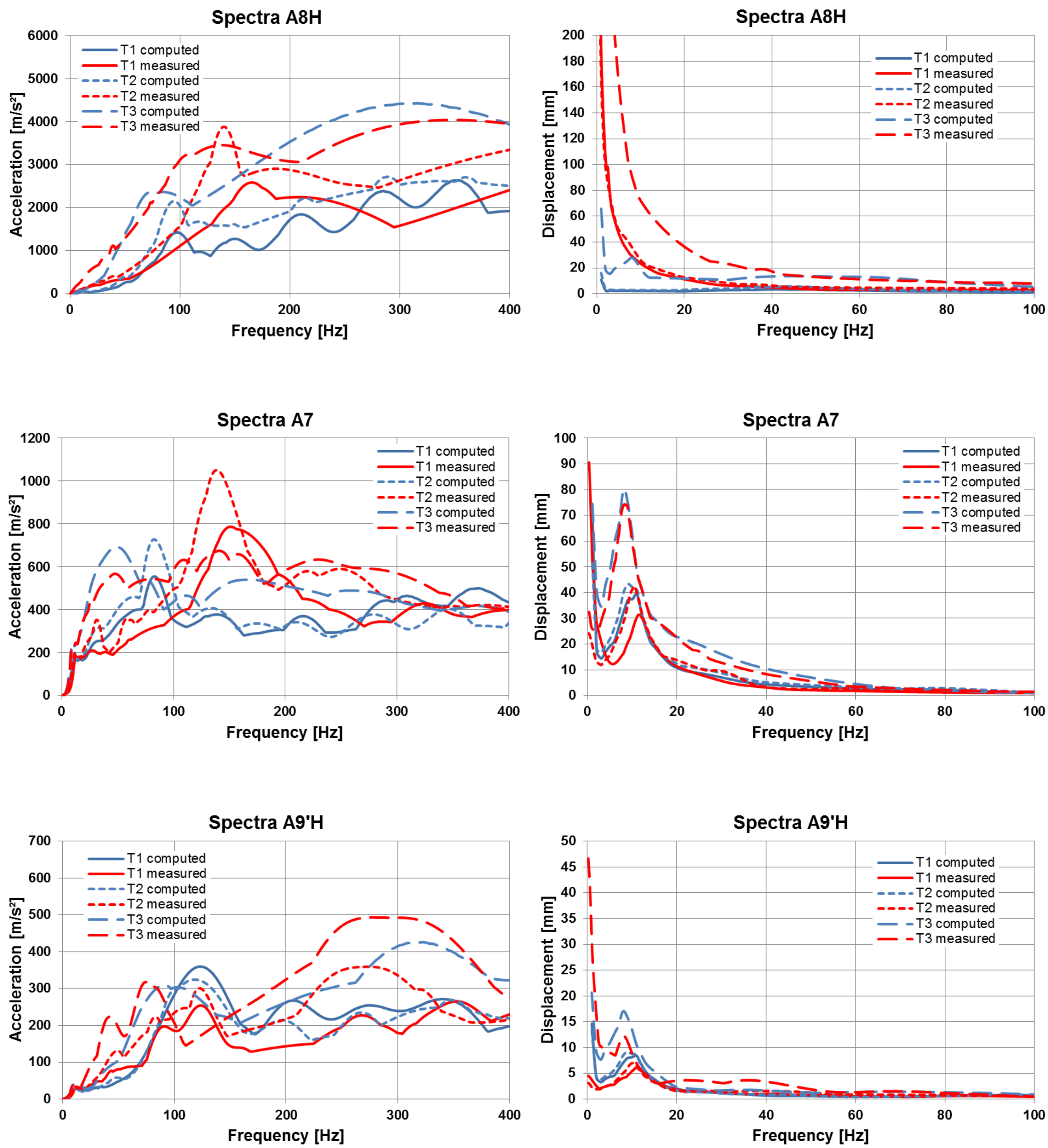


Figure 17. Comparison of selected horizontal response spectra (D = 5 %) of tests 1, 2 and 3.

CONCLUSION

The computed and measured results of the IRIS Phase 3 impact tests are of different qualities of agreement with respect to the different measured parameters and load levels reached. The comparison of measured and computed displacements results in a good agreement with respect to size as well as time progress at measuring points of the rear wall for all three tests. While this observation applies also to the displacements at the impacted front wall in the moderate tests 1 and 2, the nonlinear displacement behaviour is overestimated in the computation of test 3.

Despite filtering the accelerations above 1 kHz, due to the high frequency content mainly resulting from the measurements, an estimation of the quality of the computed accelerations is difficult. The best approximation of computed and measured acceleration spectra can be identified for frequencies below 100 Hz. From the associated displacement spectra becomes apparent that the extremely large accelerations due to the impact excitation are combined with very small displacement values, which are of minor significance for the structural integrity.

The project objective of measuring the structural damping in the areas with linear-elastic behaviour as well as in the damaged areas was not achieved up to now. The research report only states that damping of the structure increased from test to test, but drawing any other conclusions from the damping data would be very difficult.

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