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NUMERICAL SIMULATION OF EXPERIMENTS ON IMPACT INDUCED VIBRATIONS – COMPARISON OF IRIS PHASE 3 AND IMPACT V3 MOCK-UPS WITH RESPECT TO BOUNDARY CONDITIONS

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ABSTRACT

Vital parts of nuclear facilities are commonly required to resist effects of vibrations induced by external missile impact. Numerical tools used for the assessment of propagation and damping of induced vibrations are validated based on impact tests. This paper is dealing with numerical simulations using the LS-DYNA code on two impact test series with reinforced concrete mock-ups subjected to consecutive impacts of soft missiles. Both test series were carried out at Technical Research Centre of Finland (VTT). These include tests which were subject of the third phase of the benchmark activity IRIS hosted by the Nuclear Energy Agency (NEA) of OECD. Further, the test series V3 performed in the third phase of the international joint research project IMPACT is analysed. Both test series are dealing with reinforced concrete structures consisting of front wall, roof and a rear wall. Specific features of the IRIS mock-up are a cantilever wall above the rear wall, pseudo-equipment mounted to the rear wall as well as a heavy bottom slab. In both series the mock-up was mounted to the laboratory floor using the same fixation system. It was found, that for test series V3 a more detailed modelling of the fixation system was required to reproduce post impact vibration frequencies. In contrast to this, simulation results on IRIS tests turned out to be less sensitive with respect to boundary condition modelling. This is attributed to the heavy bottom slab of the IRIS mock-up, which is missing in the mock-up of test series V3.

INTRODUCTION

Impact loading of protective reinforced concrete (rc)-structures vital for the safety of nuclear facilities is a relevant loading case. The impact induced vibration propagation and damping phenomena in complex rc-structures and possible consequences for components are integral parts of safety assessments. The employed analysis software must be validated based on impact tests. This paper is dedicated to simulation results obtained with LS-DYNA software (LSTC (2020)) for validation studies performed in the third phase of the IRIS (Improving Robustness Assessment Methodologies for Structures Impacted by Missiles) benchmark hosted by the CSNI (Committee on the Safety of Nuclear Installations) of the NEA (Nuclear Energy Agency) of OECD (EdF(2018)) and in the frame of Phase III of the multinational IMPACT project (VTT(2019)). These tests were carried out by the Technical Research Centre of Finland (VTT). A description of the test facility is given by Lastunen et al. (2007). The tests discussed in this paper are dealing with consecutive soft impacts of the same type of cylindrical missile on two different box-like mock-ups. The series on the IRIS-3 mock-up includes four single tests, while two single tests were performed on the V3 mock-up. Both mock-ups were anchored to the laboratory floor with the same fixation system. A central point of the numerical study is the portability of the modelling approach chosen for IRIS tests to model V3 tests.

EXPERIMENTAL BACKGROUND

A comparison of basic geometrical dimensions and instrumentations of the two mock-ups is outlined in Figure 1. Both structures include a 150 mm thick front wall, a rear wall and a roof. In addition, the IRIS-3 mock-up features a cantilever wall above the rear wall, a 400 mm thick bottom slab and pseudo-equipment mounted to the back. Instrumentation includes sensors for accelerations and displacements. The present paper focuses on measurements at selected locations shown in Figure 1. Details on the fixation system are given below. More detailed descriptions of these mock-up and the fixation system are given below as well as by Borgerhoff et al. (2017, 2019) and EdF (2018).

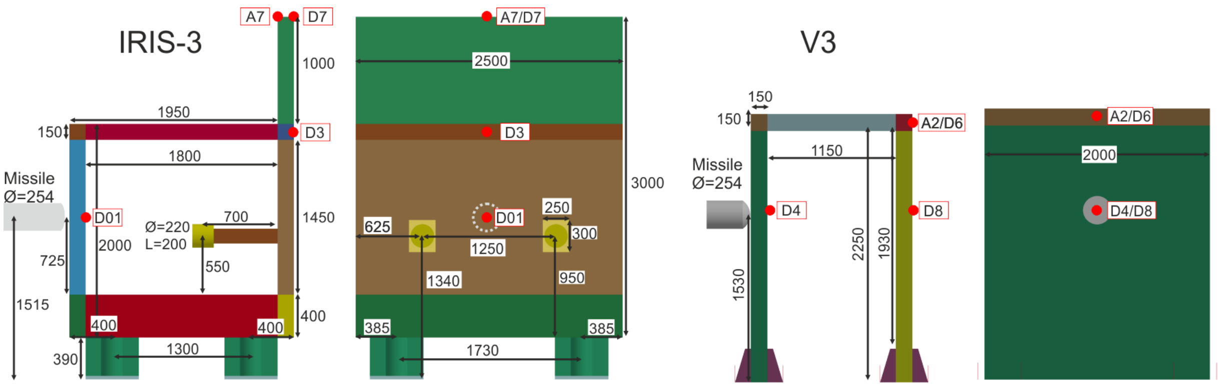

Figure 1. Dimensions and considered sensor locations of IRIS-3 and V3 mock-ups.

Table 1 summarises basic test parameters of the test sequences. In all cases the same type of cylindrical thin-walled missile (thickness t=2 mm, Ø=254 mm) with a spherical nose both made of EN 1.4432 stainless steel is used. The total length of the missile is chosen between 1500 mm and 2500 mm depending on the impact velocity, while the total mass is adjusted to a target value of about 50 kg by a heavy rear segment made of steel. In this paper tests Va and Vc from IRIS-3 and both V3 tests V3A and V3B are considered in more detail. Tests Va and V3A are supposed to result in linear elastic response, while pronounced concrete cracking and plastic deformation of reinforcement was expected in Vc and V3B.

Table 1: Test sequences with thin-walled stainless steel missiles.

Test	**Va**	**Vb**	**Vc**	**Vd**	**V3A**	**V3B**
Impact velocity / m/s	91.8	93.5	167.0	91.7	91.9	166.2
Mock-up	Va-Vc from IRIS-3, Vd from IMPACT III				V3 (from IMPACT III)	

METHODOLOGY

The tests were simulated by means of explicit Finite Element (FE) calculation using LS-DYNA (LSTC (2020)). Numerical meshes and reinforcement cages of the respective modelling setups are shown in Figure 2 for IRIS-3 and in Figure 3 for V3. Concrete is modelled using hexahedral volume elements with an average element size of 12.5 mm, reduced integration and viscous hourglass control. Properties of concrete are described by the Winfrith model (Broadhouse and Attwood (1993)) considering strain rate effects. One advantage of the Winfrith model is its usability with a limited set of input parameters, and it has been successfully employed to model slab displacements in tests on bending failure rc-slabs (e. g. Heckötter and

Sievers (2021)). Bending reinforcement is mainly included by bars of 6 mm diameter with a spacing of 50 mm on each way and each face. Shear reinforcement is used for the impacted front walls, at locations of connections between slabs and walls and at the locations of anchorages of equipment the IRIS-3 mock-up. Further, L-shaped and U-shaped reinforcement elements are used at connections of walls and slabs and at the free edge of the cantilever wall of the IRIS-3 mock-up. Every single reinforcement bar is included in the models using beam elements. They are connected to the concrete elements by means of the *Constrained_Beam_in_Solid keyword. The simplified form of the Johnson-Cook model (Johnson and Cook (1983)) available in LS-DYNA is used to describe the material behaviour of reinforcement, including strain-rate effects.

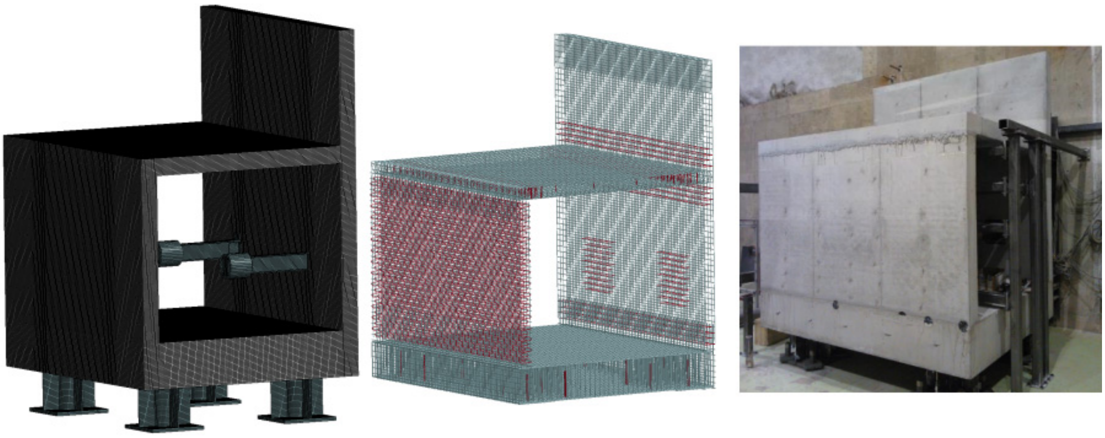

Figure 2. FE model including reinforcement cage of the IRIS-3 mock-up

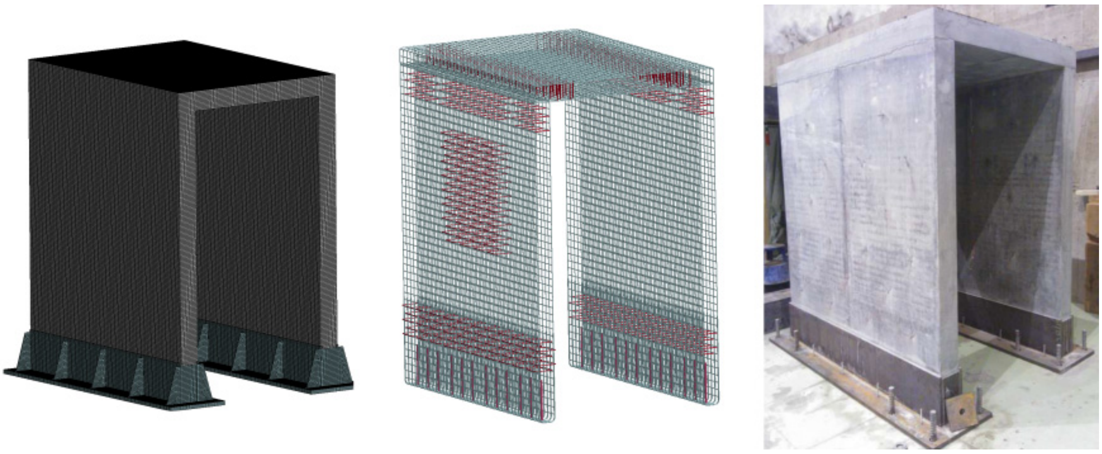

Figure 3. FE model including reinforcement cage of the V3 mock-up.

Figure 4 shows some details of the fixation system and the respective numerical models of these. The IRIS-3 mock-up is resting on four pedestal pipes which are connected by anchor plates to the bottom slab at its corners. The connection to the bottom slab is realised with four anchors (L=280 mm, Ø=25 mm) welded to each plate. The bottom plates are connected to the laboratory floor by Dywidag bars with diameter of 32 mm and length of 4.5 m. An array of 2x2 Dywidag bars at each corner of the mock-up is used, at which the holes in the laboratory floor have a diameter of about 45 mm. A 0.75 m thick layer of grouted gravel is used to stiffen the connection. Test V3 uses a structure made of steel sheets including stiffeners, which is connected to front and back wall by 16 mm diameter steel bars to front and rear wall of the mock-up. This structure is connected to the floor using the same anchorage system. In the simulation model the Dywidag bars are represented by spotweld elements with a diameter of 32 mm, which are connecting the mock-ups with the laboratory floor. The laboratory floor is modelled as a fixed rigid wall and a frictional contact is defined between mock-ups and floor. Thus, the model allows in principle nodal displacements close to the floor in vertical and horizontal direction. The effect of fastening torque was considered by the *Initial_Axial_Force_Beam keyword, where axial forces in the range of 250-450 kN were tested. It is found that results were less sensitive regarding the value of axial force, but quite sensitive to the consideration of fastening itself. In the frame of a parametric study also a simplified representation of the boundary condition with fixation of all degrees of freedom of the nodes at the location of the Dywidag bars was considered. These two modelling approaches are hereinafter called refined model and simplified model.

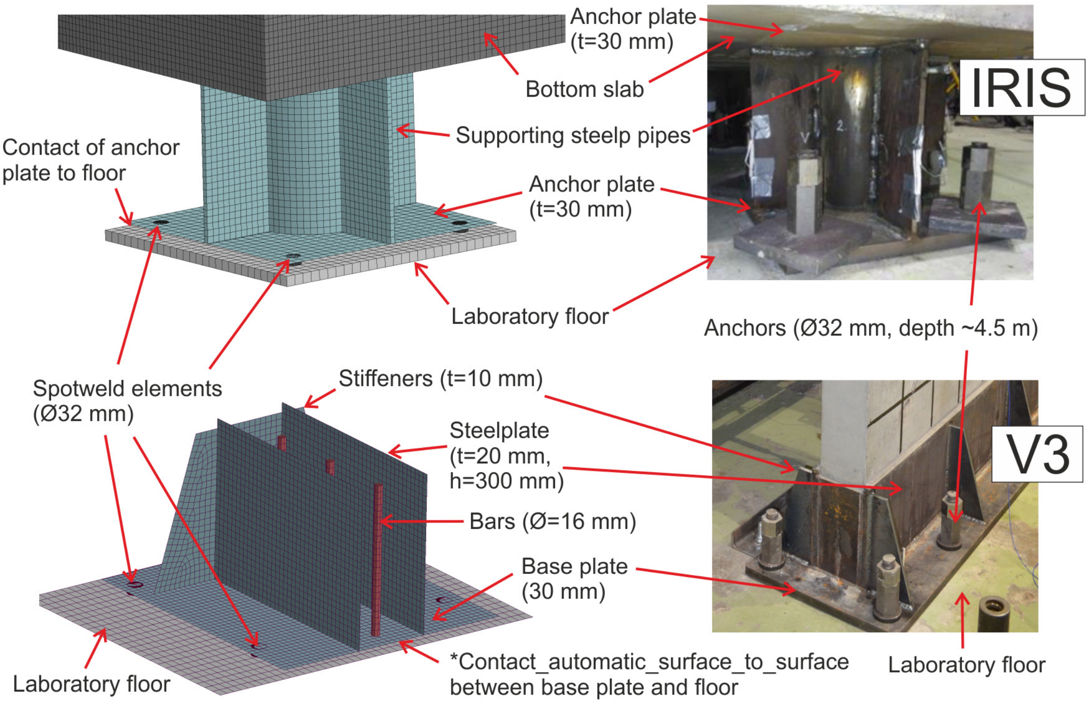

Figure 4. Details of boundary condition representation of IRIS-3 and V3 mock-ups.

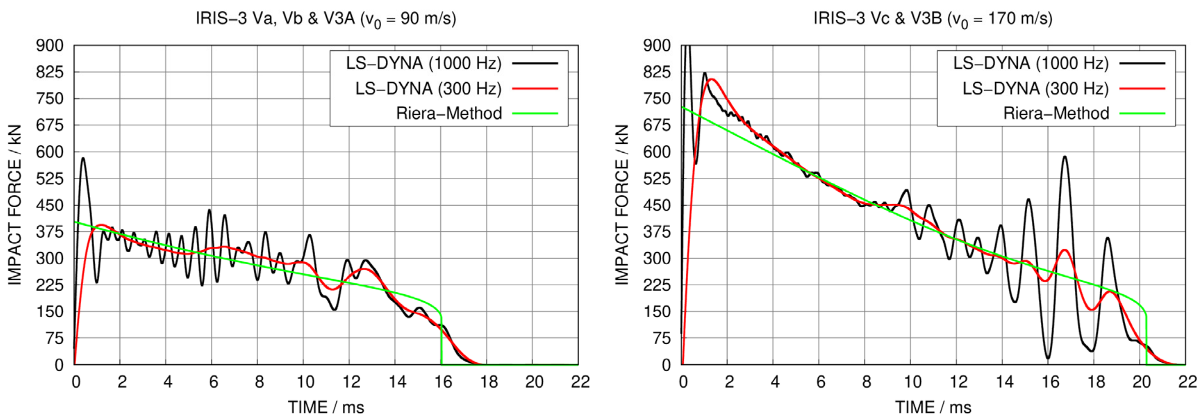

Figure 5. Comparison of load-time-functions for relevant impact velocities.

To determine the load-time functions (LTFs), simulations of the missile structure represented by shell elements impacting a rigid target were carried out. Figure 5 compares low-pass filtered contact forces with results obtained by the so-called Riera method (Riera(1968)) for the two relevant impact velocities. Modelling parameters of the missile as well as assumptions for the crushing force used for the Riera method are given elsewhere (Heckötter and Sievers (2015)). Regarding impact duration and average impact forces the results agree reasonably well. Further, simulation results are consistent with test data regarding the crushing of the missile. In the present study, 1 kHz low pass filtered contact forces were applied to the mock-ups as evenly distributed time-dependent pressure to a circular area corresponding to the footprint of the missile. Mayor advantage of the LTF approach compared to the missile-target-interaction (MTI) method is numerical stability for longer simulation times. Further, the effect of gravity is included. A typical simulation run starts with application of gravity and a dynamic relaxation realised by a global static damping. Consecutively a LTF is applied followed by a certain time of post impact vibration. Further LTFs are applied after another dynamic relaxation. Despite hourglass damping and damping effects due to material damage and plastic deformation no further damping is applied during the impact simulations.

RESULTS

The Winfrith model enables crack visualization in the post-processing phase. Figure 6 compares calculated crack patterns in the tests IRIS Vc and V3B with photographs of the mock-up, where cracks were highlighted with a fluid. In principle, the crack patterns are realistically reproduced by the Winfrith model. Pronounced cracking occurs at the centre of the front wall. Further cracking is observed at the connections of slabs and walls. Test data from strain gauges glued to the reinforcement and numerical results indicate plastic deformation of reinforcement at these locations. In the tests IRIS Va and V3A only minor cracking and no plastic deformation of reinforcement is observed.

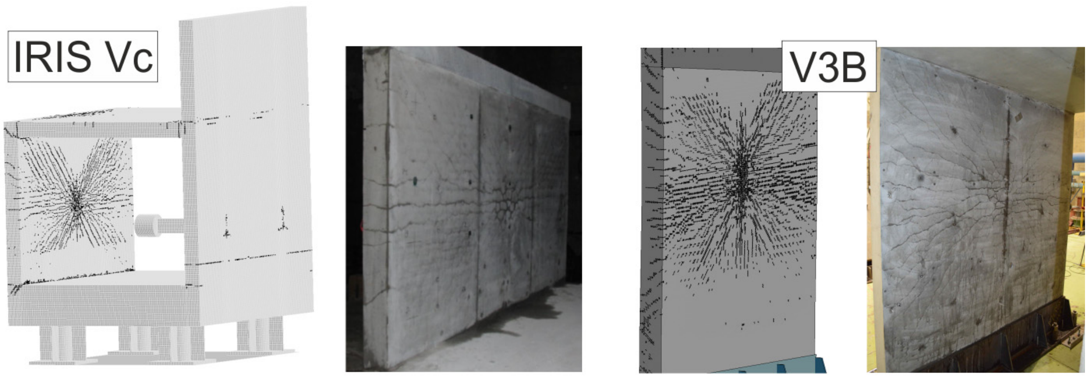

Figure 6. Simulated and observed crack patterns of the front walls after tests IRIS Vc and V3B.

A comparison of measured and calculated horizontal displacements at selected sensor locations (see Figure 1) is given in Figure 7 for the IRIS tests and in Figure 8 for test V3. Positive values indicate a displacement in the direction of the initial velocity of the missile. In principle, the simulation results reproduce very well the test data regarding ultimate elongation and post impact vibration frequency. As expected, the largest displacements occurred at position of D7 the top of the cantilever wall, since it this the sensor located at maximum height of the mock-up. Some underestimations of displacements measured in test Va appear for sensor D01 at the centre of the front wall, which can be attributed to the load application by means of LTF rather than MTI. Test simulation yielded, that displacements at other locations turned out to be less sensitive to the method of load application. Further, some underestimation of the maximum displacement calculated at position of D3 at the connection of roof slab and rear wall is visible in the comparison. In principle results are not that sensitive regarding the level of detail used for the representation of boundary conditions. As expected, the simplified model seems to be slightly stiffer than the refined one. This is most noticeable in test Vc at the location of D01. An evaluation of nodes near the anchorage of the mock-up to the laboratory floor showed, that only small displacements in the order of fractions of one millimetre are calculated by the refined model, which is attributed to the 400 mm thick bottom slab of the IRIS-3 mock-up. This applies for horizontal as well as for vertical displacements.

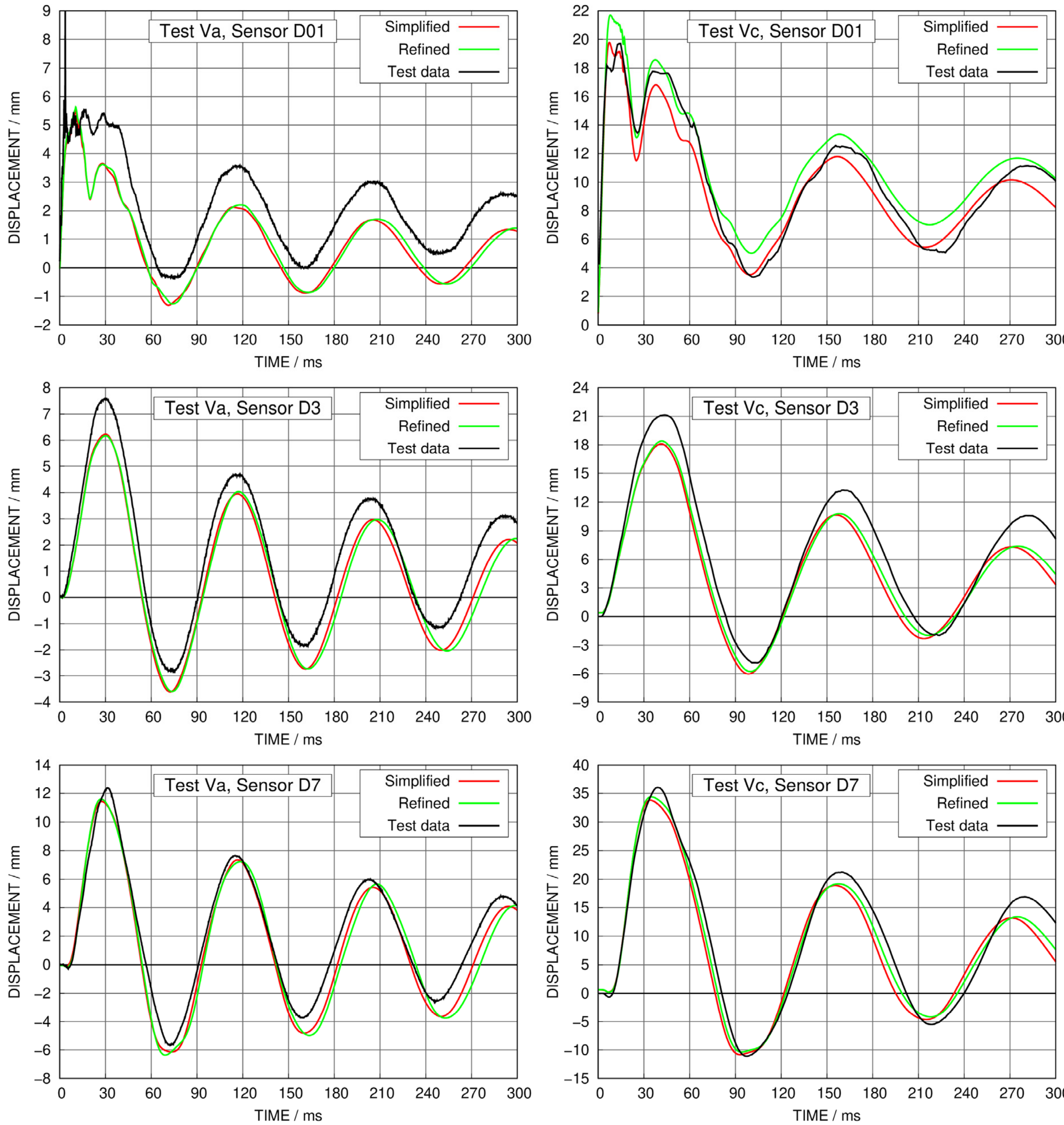

Figure 7. Calculated and measured horizontal displacements at selected locations in tests IRIS Va and Vc.

A similar comparison of measured and calculated displacements for test V3 is given in Figure 8 with sensor locations illustrated in Figure 1. The refined model reproduces very well the test data regarding elongation and frequency for test V3A, which are supposed to correspond to mainly linear-elastic material behaviour outside the impacted area. In contrast to this, the response of the simplified model is stiffer and also some underestimation of maximum elongation occurs. For test V3B the same conclusions apply, but the frequency of post impact vibration is also overestimated by the refined model. This is related to an underestimation of damage by both models. In contrast to IRIS-3 tests larger vertical displacements close to the fixation system of 2 mm in V3A and 4 mm in test V3B were calculated with the refined model. These relatively large values compared to results of IRIS-3 simulations are attributed to the absence of the bottom slab in V3. The simplified model is not capable to reproduce these displacements. Only small horizontal displacements below 0.2 mm were calculated close to the fixation system. It is concluded that vertical displacements are more relevant than horizontal displacements in the lower region of the V3 mock-up.

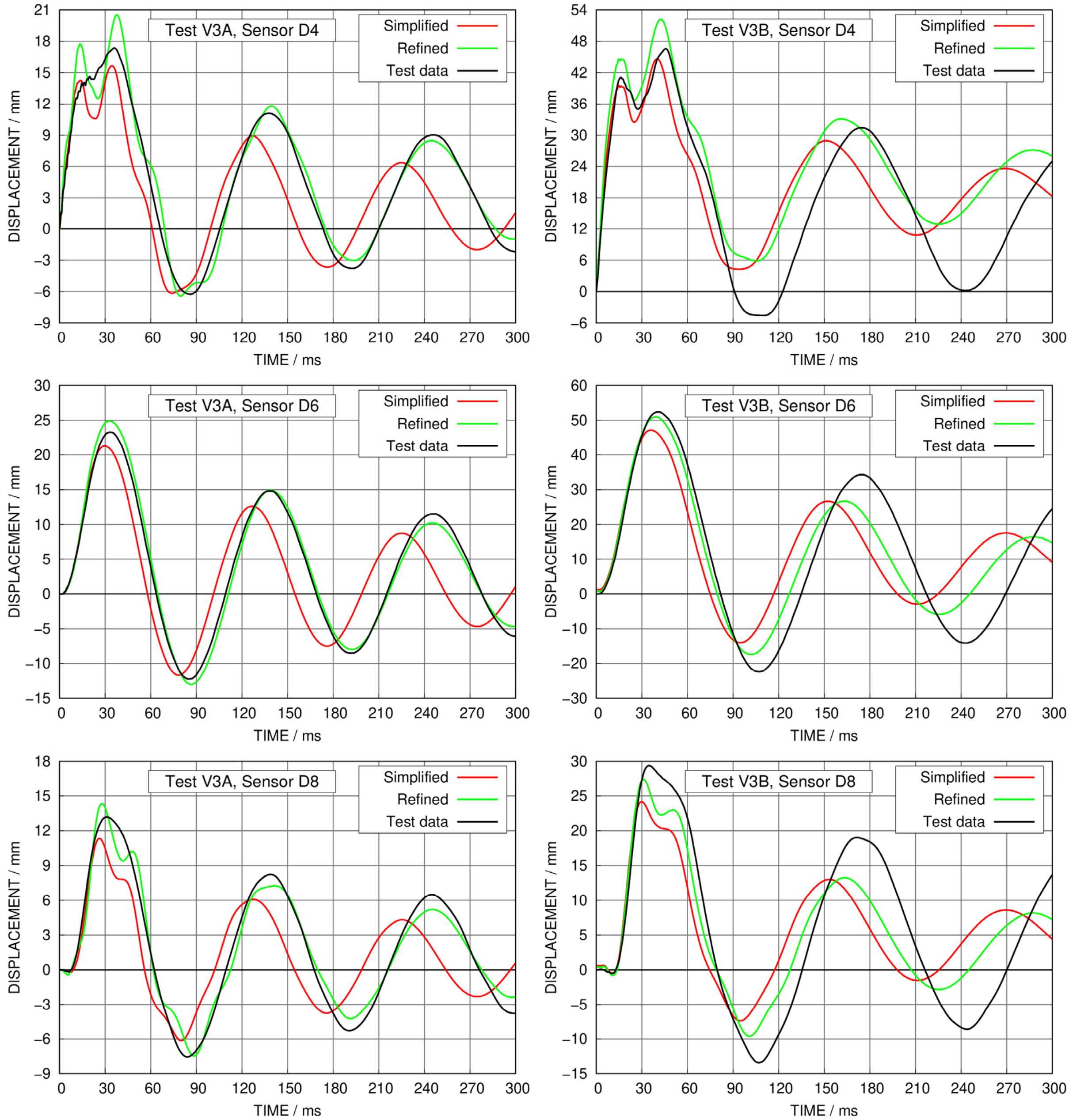

Figure 8. Calculated and measured horizontal displacements at selected locations in tests V3A and V3B.

A comparison of measured and simulated time-histories of accelerations of test IRIS-3 at the position of sensor A7 is given in Figure 9. Sensor A7 is located on the front face at the top of the cantilever wall (see Figure 1). A corresponding comparison for test V3 is given in Figure 10 at the position of sensor A2. All signals were low-pass filtered with a cut-off frequency of 1 kHz. Especially for test V3 numerical results show some higher frequency content which is not visible in the test data. It is attributed to the FE-discretisation and sudden loss of stiffness in cracked elements.

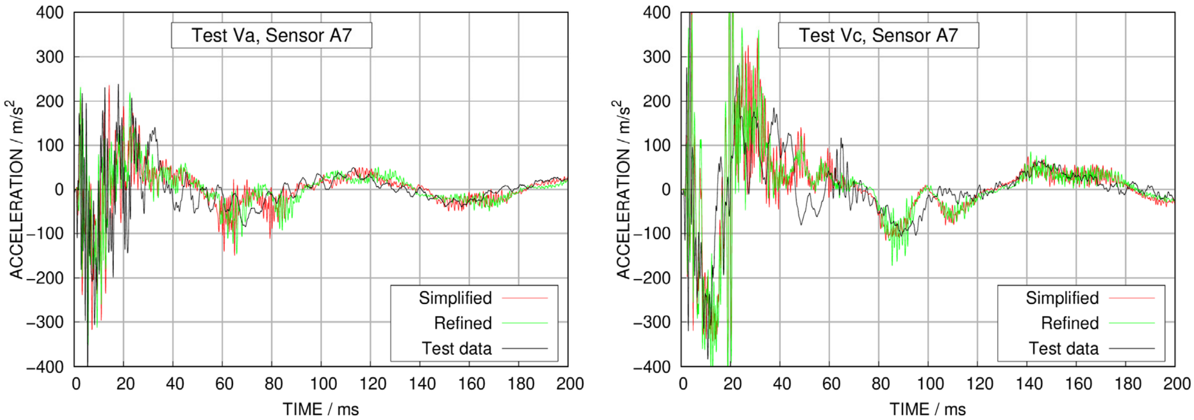

Figure 9. Calculated and measured accelerations at sensor A7 in IRIS Va and Vc.

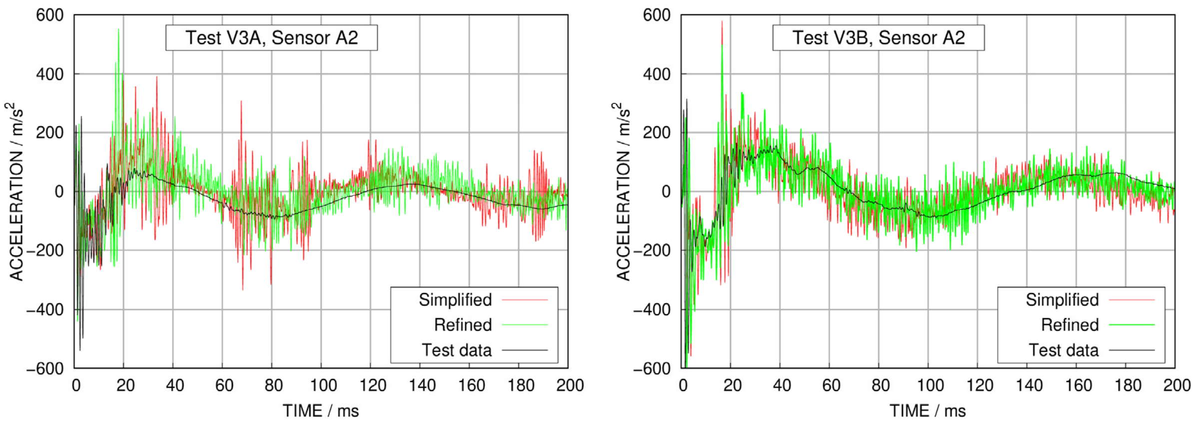

Figure 10. Calculated and measured accelerations at sensor A2 in V3A and V3B.

A comparison of spectral displacements calculated from time-histories of horizontal accelerations is given in Figure 11 for IRIS-3 and in Figure 12 for V3 tests, at which a value of 5% of critical damping was used. All curves include a peak which is related to a vibration mode of the whole mock-up in horizontal direction. It is apparent that results of both models are very similar for IRIS-3 tests. In contrast to this the effect of boundary condition in test V3 is clearly visible. The reduction of stiffness due to damage of the structure is correctly predicted for IRIS-3 Vc, while it is underestimated for V3B, especially with the simplified model. These findings are consistent with results on displacements shown in Figure 7 and Figure 8. It is therefore concluded that a more realistic modelling of concrete cracking and yielding of reinforcement might improve the results for V3B.

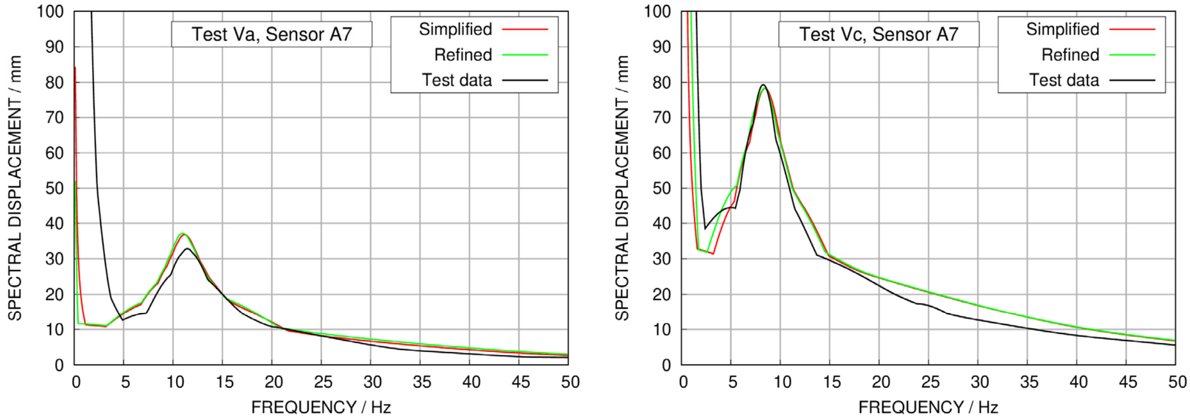

Figure 11. Spectral displacements for 5% of critical damping at sensor A7 in IRIS Va and Vc.

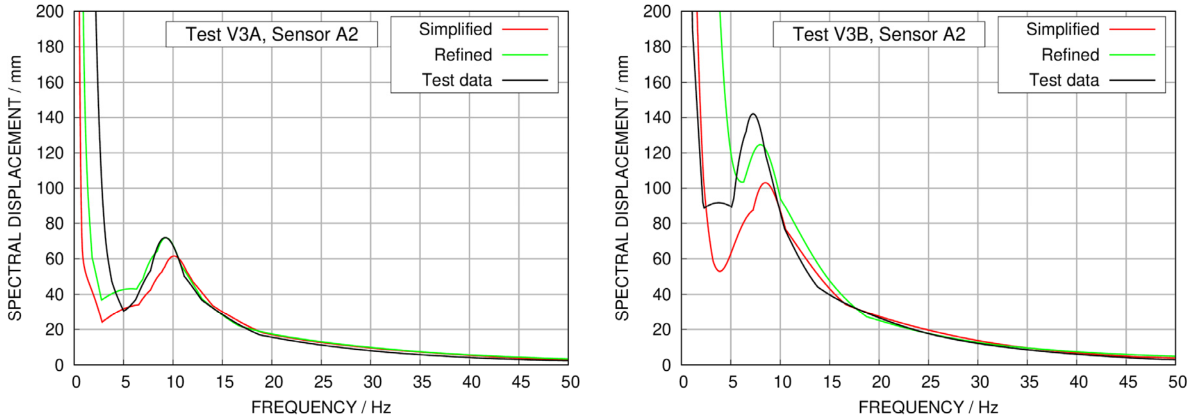

Figure 12. Spectral displacements for 5% of critical damping at sensor A2 in V3A and V3B.

CONCLUSION

The Winfrith concrete model available in LS-DYNA is well suited to reproduce displacements measured in impact tests IRIS-3 and V3 related to induced vibrations in rc-structures subjected to consecutive impacts of soft missiles.

Calculation results on the IRIS mock-up were not very sensitive regarding boundary condition modelling. A simplified and a refined model reproduce very well test results on displacements and floor-response spectra. In contrast to this a good reproduction of test results for V3 required a more detailed modelling of the boundary condition. This is attributed to larger vertical displacements in lower regions of the V3 mock-up. Similar displacements did not occur for the IRIS tests due to the heavy bottom slab of that mock-up.

With a refined modelling of the boundary condition, the representation of test data is significantly improved for test V3A dealing with linear-elastic behaviour of the mock-up. The reduction of stiffness of the mock-up is underestimated in V3B simulations, even with the refined model. A more realistic modelling of concrete cracking and yielding of reinforcement may improve the results on test V3B.

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