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Division V

IMPACT INDUCED VIBRATIONS OF REINFORCED CONCRETE STRUCTURES DETERMINED BY LINEAR AND NONLINEAR ANALYSES OF TESTS PERFORMED WITHIN IMPACT III PROJECT

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ABSTRACT

The IMPACT project is organised and carried out by the VTT Technical Research Centre of Finland in Espoo (Finland) and funded by several institutions including the Swiss Federal Nuclear Safety Inspectorate ENSI. As part of Phase III of the project, the test series V was carried out, which pursued the objective of investigating the influence of nonlinear structural behaviour on the induced vibrations of reinforced concrete (RC) structures and their damping. Based on the test data, the capabilities of current finite element (FE) techniques should be demonstrated in terms of simulating the vibration propagation and damping behaviour of a RC structure, which is subjected to nonlinear deformations caused by an impact of a deformable missile, cf. Borgerhoff et al. (2015).

The objective of the last test in this series (V3) was to obtain further data with regard to the propagation and damping of vibrations by use of a preferably simple system with most clearly defined boundary conditions. Numerical analyses of the two consecutive impact tests, which have been carried out with the V3 mock-up, are evaluated in this paper. In addition to the primarily performed nonlinear analyses, comparative analyses assuming linear material behaviour are carried out in order to receive information about the differences when applying this less expensive method for the determination of floor response spectra.

INTRODUCTION

The research project IMPACT III is organised and carried out by VTT and funded by several institutions including ENSI. The aim of the IMPACT III project is to develop experimental data and information on physical phenomena occurring during an aircraft impact on a RC structure. One focal point of the participation of ENSI and their consultants Stangenberg & Partners in this project lies in the support in planning of the mock-ups for use in a test series dedicated to the influence of nonlinear structural behaviour on the induced vibrations of RC structures and their damping. In detail, this specific test series consists of the tests V0, V1, V2 and V3. The experimental setups of each test were used for a number of consecutive impacts.

Based on the experience with the preceding tests, the mock-up of test V3, which is the subject of this paper, was intended to be a preferably simple system with most clearly defined boundary conditions. Especially the numerical simulation of test V1 proved to be difficult because of unintended effects caused by the supports of the mock-up, cf. Borgerhoff et al. (2015).

EXECUTION OF TEST V3

The mock-up of test V3 was designed according to proposals of ENSI and its experts. It has the shape of a clamped RC frame, which consists of 2.0 m wide and 2.4 m high front and rear walls and a connecting roof plate with 1.45 m length, see Figure 1. The RC structure has a uniform wall thickness of 0.15 m.

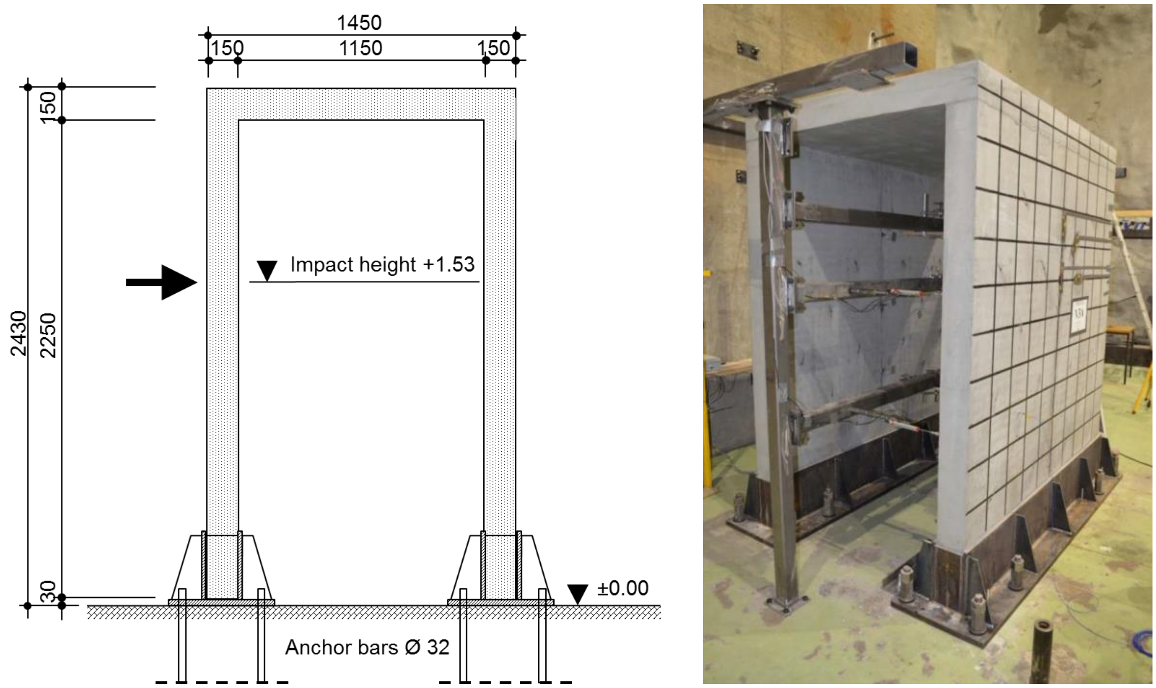

Figure 1. Side view (left) and photo of the mock-up of test V3 with supporting structure (right)

The concrete quality used for the mock-up is C40/50 with a maximum aggregate size of 8 mm. The basic reinforcement of walls and ceiling consists of rebars B500B with diameter 6 mm and spacing 50 mm. The lower parts of the walls are additionally reinforced with diameter 10 mm U-shaped bars. Shear reinforcement consisting of diameter 6 mm hooked stirrups is installed in the area around the hit point and in the regions of the joints between the walls and the ceiling as well as the supports.

The supports of the mock-up are box-shaped steel sheet constructions as shown in Figure 1. They are fixed to the same anchors as the mock-up, which was tested in phase 3 of the IRIS benchmark project, cf. Borgerhoff et al. (2017 and 2019). The lower ends of the mock-up walls are inserted in these supporting structures and linked to them by diameter 16 mm rebars, which are welded on the base plates. The supporting structures are anchored by means of 4 times 4 Dywidag rock anchors diameter 32 mm, which are embedded in the rock below the floor of the experimental hall. The diameter of the clearance holes in the base plates is 45 mm.

The mock-up was tested for two consecutive impacts by two types of tubular projectiles with 50 kg mass, 254 mm diameter, 2 mm wall thickness as well as 1.5 m pipe lengths in test V3A and 2.5 m in test V3B, respectively. The impact velocities were 91.9 m/s (V3A) and 166.2 m/s (V3B).

NUMERICAL SIMULATIONS

Computer model

The dynamic analyses by use of the computer code SOFiSTiK (2014) are carried out with the FE model shown in Figure 2. The shell elements used for modelling the reinforced concrete structure include a nonlinear, layered material model with approximate consideration of nonlinear shear deformations. Slabs and walls are subdivided into 12 concrete layers, and the crosswise reinforcement at both sides of the structural elements is considered. Rayleigh damping was used as damping model for all elements. The Rayleigh coefficients were calculated providing for 1% critical damping in the relevant frequency range.

The supporting structures made of steel sheets are modelled by shell elements, which are connected with the concrete structure and the floor by nonlinear contact springs. The rock anchors are modelled by spring elements, see Figure 2. In the contact surfaces of base plates and floor as well as walls and steel sheets, only compressive force transmission is allowed in the calculation. The vertical spring elements representing the anchors allow only the transmission of tensile forces. The capability of the anchors in transmission of transverse forces is determined following the typical nonlinear behaviour of studs by use of parametric analyses depending on the different load levels in the tests V3A and V3B. The stiffnesses of the horizontal spring elements are adjusted to the observed behaviour of the mock-up.

In a further parameter analysis, the free length of the grouted rock anchors, which defines the stiffness of the vertical springs, is varied between 1.38 m and 3.70 m. This variation does not imply significant changes in the results. In this respect, the definition of the horizontal spring stiffnesses is decisive.

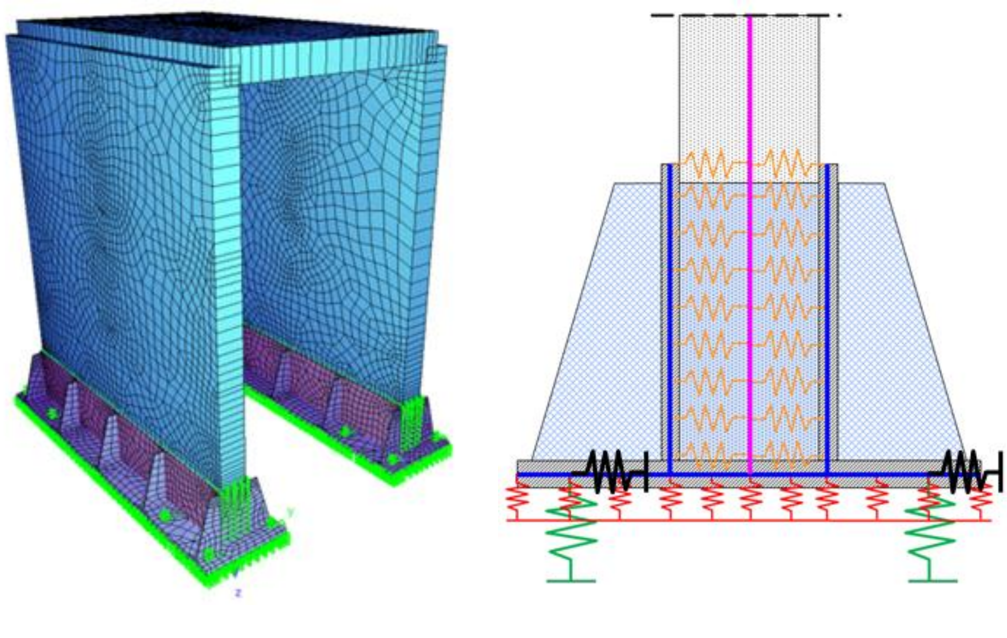

Figure 2. Mock-up of test V3 and finite element (FE) model.

Load time functions

The load time functions used for the computations are the same as in phase 3 of the IRIS benchmark project since the same types of projectiles with almost equal impact velocities were used also in the tests V3A and V3B, cf. Borgerhoff et al. (2019). Their graphs are shown in Figure 3.

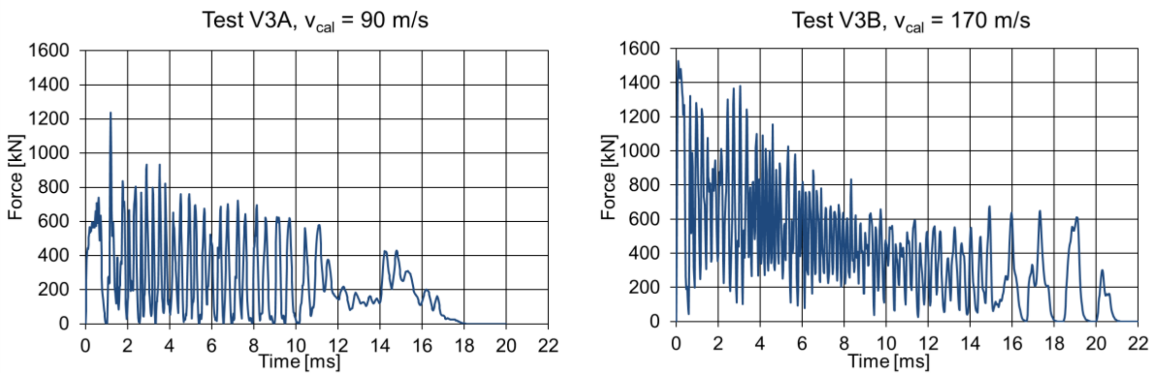

Figure 3. Calculated load time functions of tests V3A and V3B.

Linear and nonlinear calculations

The dynamic analyses are carried out by use of the computer code SOFiSTiK (2014). The physically and geometrically nonlinear structural behaviour is taken into account. In addition to these primarily performed nonlinear calculations, comparative analyses assuming linear material behaviour are carried out. These calculations have the objective of obtaining information about the differences when applying this less expensive analysis method for the determination of floor response spectra.

Comparison of computed and measured results

The results are presented in form of diagrams containing time functions and response spectra of the computed and measured parameters. The installed monitoring system comprises displacement, strain and acceleration sensors. Response spectra were derived from the computed and measured accelerations. The locations of the displacement and acceleration measuring devices, which were chosen for this evaluation, are shown in Figure 4.

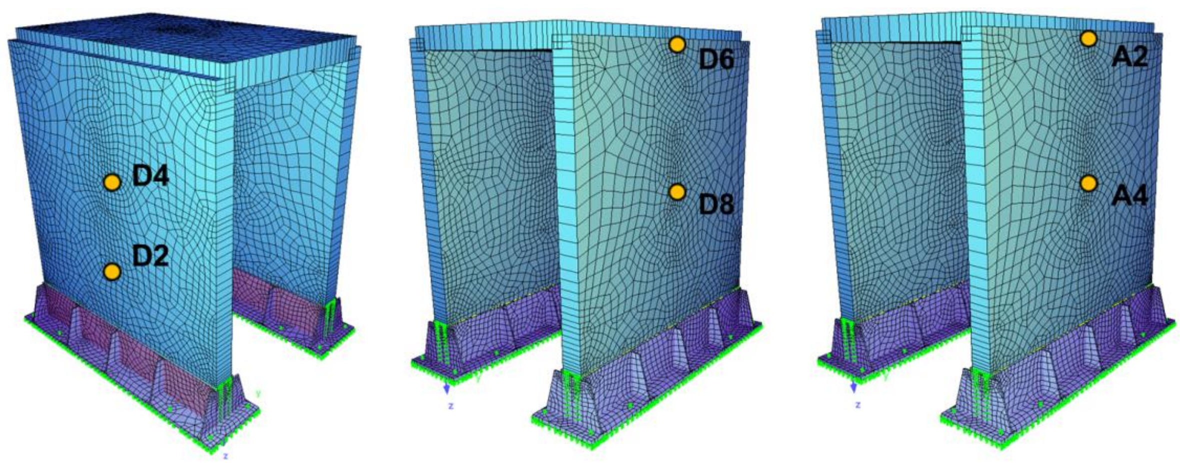

Figure 4. Evaluated displacement sensors (left: at front wall, centre: at rear wall) and accelerometers (right: at rear wall).

The diagrams presented hereinafter contain three curves each. The blue lines show the measured displacements and accelerations. The calculated results generated by nonlinear and linear calculations are depicted through black solid lines (nonlinear) and black dotted lines (linear).

In the test with the lower impact velocity (V3A), only minor nonlinear deformations in the impact zone and primarily linear-elastic global behaviour were expected. Under the high impact velocity (V3B), comprehensive cracking and plastic steel strains were predicted. Figure 5 and Figure 6 (V3A) as well as Figure 7 and Figure 8 (V3B) show the time histories of the horizontal displacements at the locations defined in Figure 4. The time histories show in course and magnitude a mainly good agreement between measurement and nonlinear calculation. The displacements measured in the upper half of the mock-up height are reproduced well by calculation. In the lower part they are overestimated, see data of sensor D2 depicted in Figure 5 and Figure 7.

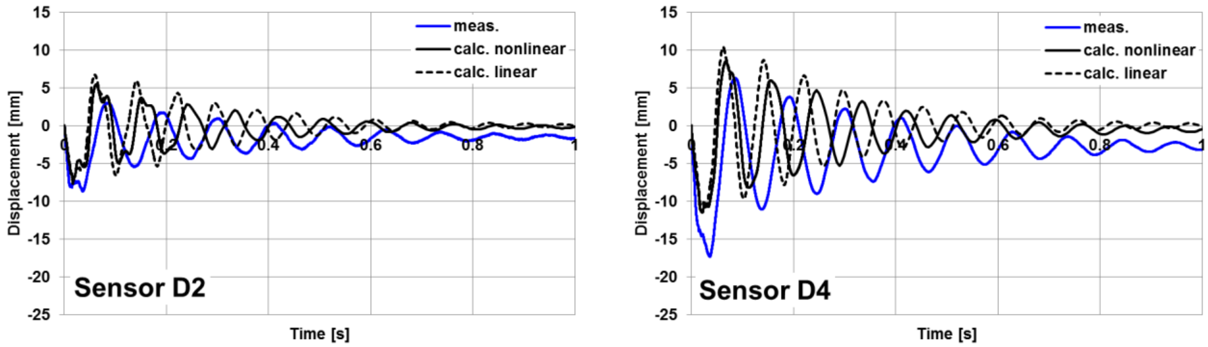

Figure 5. Test V3A (90 m/s), horizontal displacements of sensors D2 and D4.

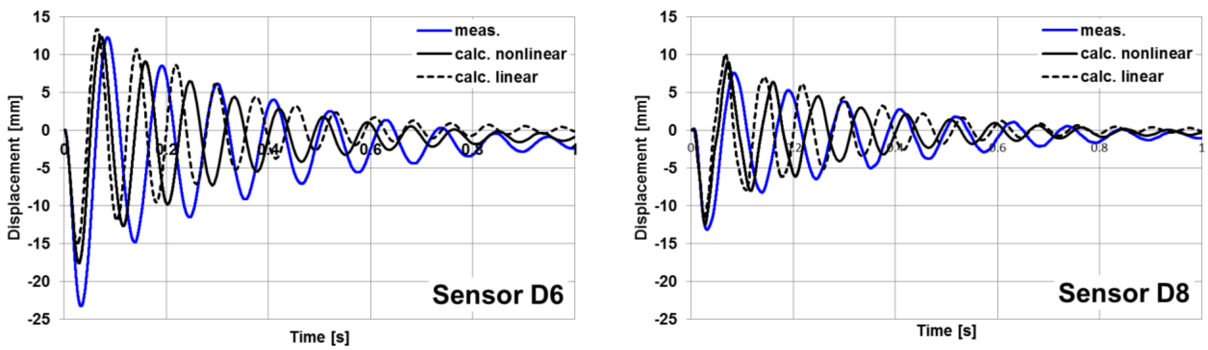

Figure 6. Test V3A (90 m/s), horizontal displacements of sensors D6 and D8.

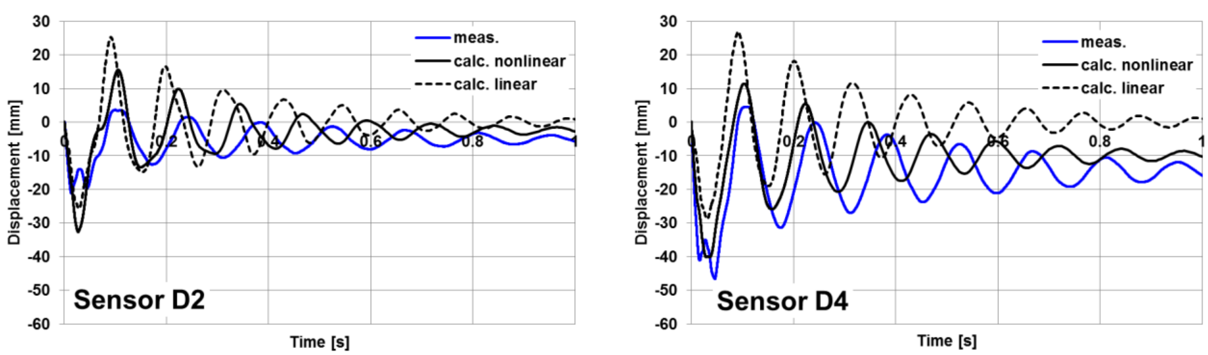

Figure 7. Test V3B (170 m/s), horizontal displacements of sensors D2 and D4.

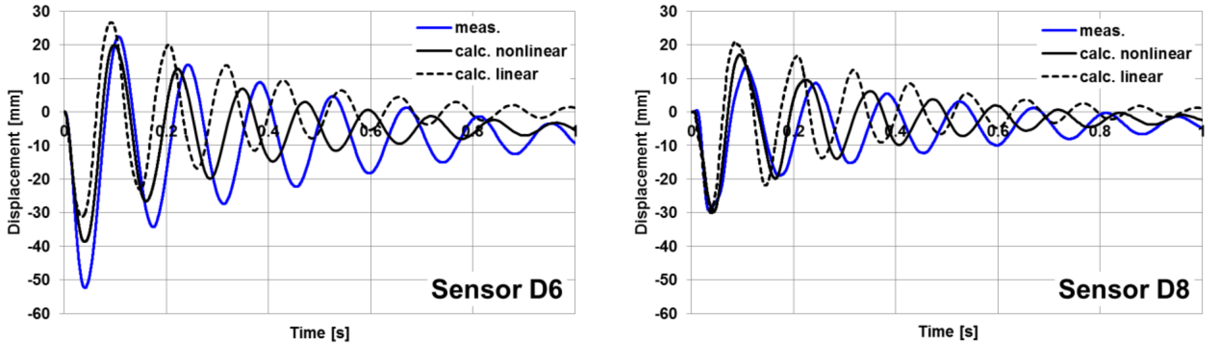

Figure 8. Test V3B (170 m/s), horizontal displacements of sensors D6 and D8.

As expected, the differences between nonlinearly and linearly calculated displacements are small in test V3A. In test V3B, the differences mainly arise from the shift of the nonlinearly calculated curves due to the residual plastic deformations.

The measured and calculated acceleration time histories are compared with each other in Figure 9 (V3A) and Figure 10 (V3B). The measured acceleration time histories are filtered in terms of the fraction above 1 kHz. Apart from differences due to numerical inconsistencies the measurements are reasonably reproduced by way of calculation.

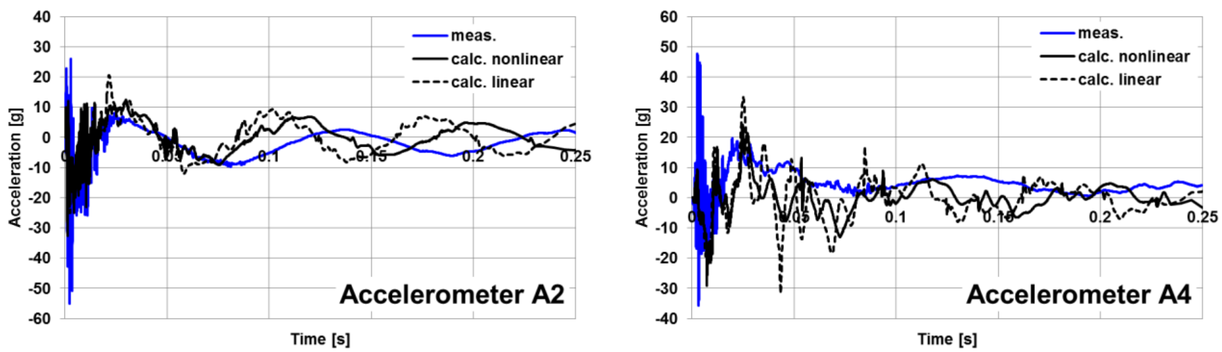

Figure 9. Tests V3A (90 m/s), horizontal accelerations of sensors A2 and A4.

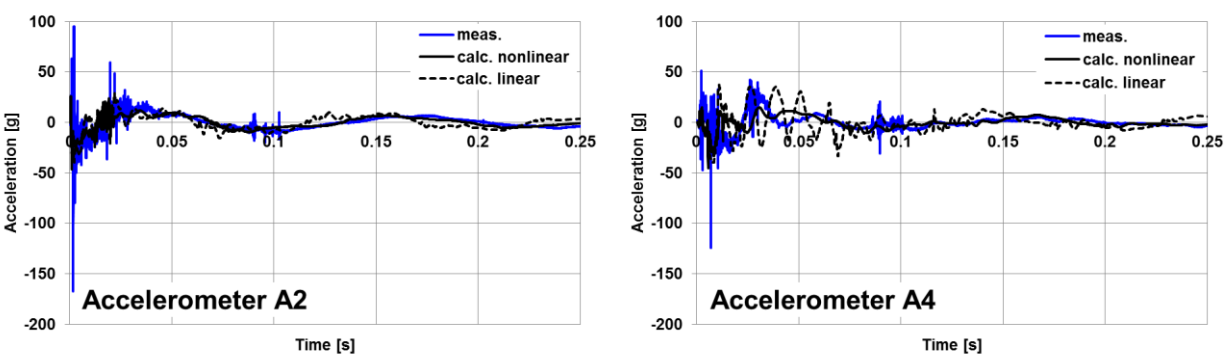

Figure 10. Test V3B (170 m/s), horizontal accelerations of sensors A2 and A4.

Floor response spectra are computed from the measured and calculated acceleration results adopting 5% damping. Acceleration response spectra of the measuring positions at the rear wall are shown in Figure 11 (V3A) and Figure 12 (V3B). Particularly in test V3B, the measured spectra are well represented by the nonlinear calculations. The linear spectra are higher than the nonlinear ones up to different degrees. Location A4 exhibits particularly strong deviations above 70 Hz.

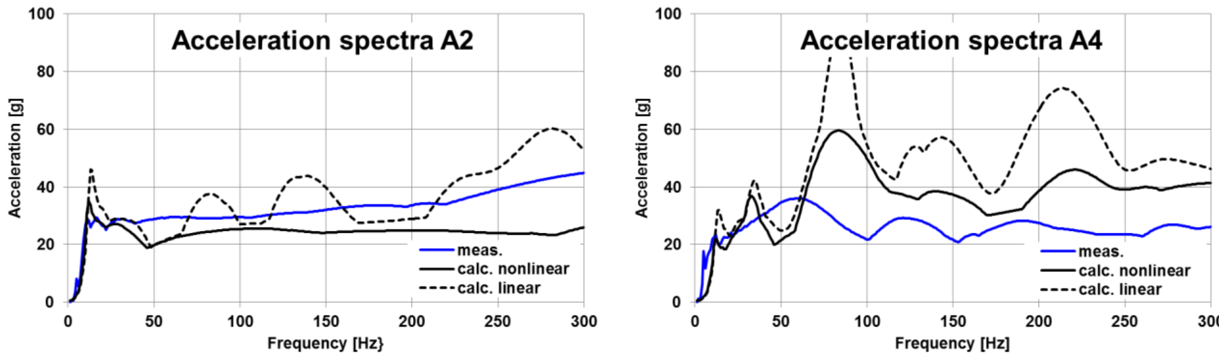

Figure 11. Test V3A (90 m/s), horizontal acceleration response spectra at locations A2 and A4.

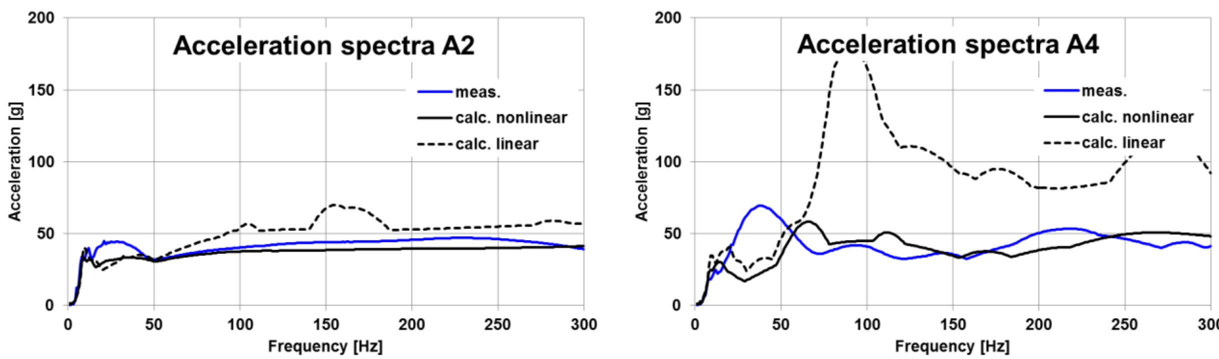

Figure 12. Test V3B (170 m/s), horizontal acceleration response spectra at locations A2 and A4.

Displacement response spectra of the measuring positions at the rear wall associated to the acceleration spectra discussed previously are shown in Figure 13 (V3A) and Figure 14 (V3B). The displacement spectra D6 at ceiling height, which are dominated by the global vibration behaviour of the mock-up, are underestimated by the computed results.

At location D8, the displacement spectra are influenced by the plate oscillations of the rear wall. These spectra are well matched by the nonlinear calculations. And the linearly calculated results are perceptibly larger than the nonlinearly calculated.

Causes of deviations between measured and calculated results

The measurement results of test V3 suggest that larger horizontal relative displacements in the order of several millimetres occurred between the steel supports of the mock-up and the floor of the test facility. As can be seen from Figure 15, the condition of the grouting of the rock anchors after all vibration propagation and damping tests within the projects IMPACT III and IRIS Phase 3 does not show any damage. The fine radial hairline cracks are no indication for the observed larger displacements.

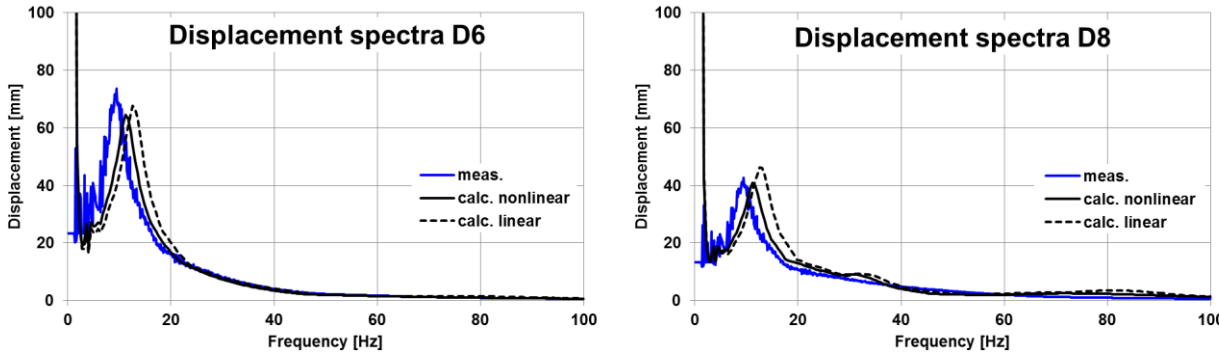

Figure 13. Tests V3A (90 m/s), horizontal displacement response spectra at locations D6 and D8.

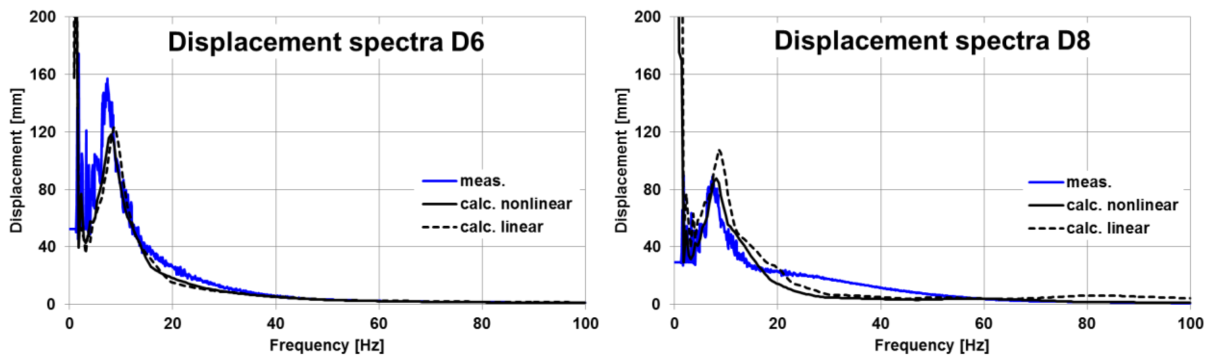

Figure 14. Test V3B (170 m/s), horizontal displacement response spectra at locations D6 and D8.

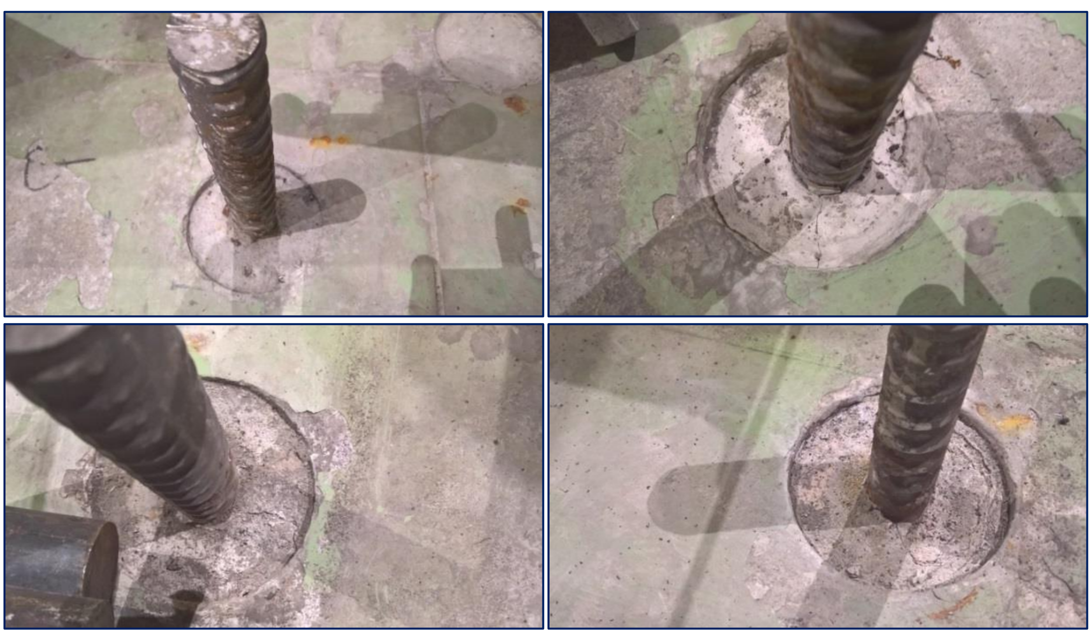

Figure 15. Condition of grouted anchorage bolts after all IMPACT III and IRIS Phase 3 tests.

Larger horizontal displacements of the mock-up were possible due to the diameter 45 mm of the clearance holes in the base plates, which are considerably larger than the diameter 32 mm of the Dywidag rock anchors. Unfortunately, they have not been measured since displacement sensors were not installed at the level of the supports. The ability of slippage has been considered in the presented calculations by way of horizontal spring elements adjusted to the observed behaviour of the mock-up.

CONCLUSION

The objective of the last test in the IMPACT III series dedicated to the investigation of the vibration and damping behaviour of RC structures (V3) was to obtain further data by use of a preferably simple system with most clearly defined boundary conditions. Due to unexpected slippage between the base plates of the steel supports of the mock-up and the anchorage bolts, the calculated deformations had to be adjusted to the observed vibration behaviour by specification of transverse anchor stiffnesses depending on the load levels in the two sub-tests V3A (90 m/s) and V3B (170 m/s). In this respect, the set goal of a simple system was not fully achieved.

The applied material laws are based on the original data of the material tests for concrete and steel. Apart from the flexible support, the test structure itself appears to be less stiff than presumed in the FE analysis. For sensors above height ~1.3 m, the displacements are simulated by the SOFiSTiK FE model almost in accordance with the measurements. The displacements below this level are overestimated by the analysis particularly in case of test V3B.

The computed accelerations are almost in accordance with the measurements. Only the measured maximum peak values in the first 20 ms in spite of filtering show relatively strong deviations. In particular the calculated displacement spectra are well matching the spectra determined by use of the measured displacements.

From the linear calculations performed for comparison, it is clear that this less complex calculation method usually leads to results that are on the safe side. With only slight plastic deformation, the differences are small. However, the differences are so large at higher actions with significant plastic deformations that the increased effort of a nonlinear spectral determination is worthwhile.

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