Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division V

NUMERICAL SENSITIVITY STUDIES ON VIBRATION PROPAGATION AND DAMPING

Arja Saarenheimo[1], Kim Calonius[2], Alexis Fedoroff[3], Markku Tuomala[4] and Ari Vepsä[5]

[1] Research Team Leader, VTT Technical Research Centre of Finland Ltd
[2] Senior Scientist, VTT Technical Research Centre of Finland Ltd
[3] Research Scientist, VTT Technical Research Centre of Finland Ltd
[4] Prof. emeritus, Consultant, Finland
[5] Senior Scientist, VTT Technical Research Centre of Finland Ltd

ABSTRACT

A test series called V1 considering vibration propagation has been carried out at VTT. A reinforced concrete structure with two parallel walls connected to a floor slab was impacted with a deformable stainless steel missile with a mass of 50 kg onto the middle of the front wall. The front wall is strengthened with triangular side walls connected to the floor slab. The structure is vertically supported on elastomeric bearing pads and with tension bars and horizontally supported with steel back pipes and tension bars. In order to obtain information on vibration propagation in damaged concrete structure at different levels of damage grades the same structure was tested six times. In tests V1A-D the impact velocity was about 110 m/s, whereas in tests V1E and F it was 60 m/s.

In this paper, the results of numerical sensitivity studies on the first test, V1A, are presented and discussed. Sensitivity studies are carried out on essential damping and modelling assumptions affecting vibration propagation properties. In an Abaqus shell element model non-linear behaviour of shell section is modelled by dividing the cross section into layers. Reinforcements are also modelled as layers. The impact load is introduced to the structure either as a loading function or by modelling the impacting missile with shell elements. In a second Abaqus model eight noded solid elements are used in the impact zone and reinforcements are modelled with beam elements. The concrete damage plasticity model is adopted in both Abaqus models.

Deflection and strain histories and response spectra values computed from acceleration histories obtained with different computational models are compared with the experimental findings.

INTRODUCTION

The primary task of protective walls is to keep possible impacting projectiles and burning fuel outside the building housing vulnerable equipment and to protect them against external loads. The design of safety related structures considering possible vibration isolation, e.g. nuclear power plants, requires reliable analysis methods that are verified against relevant test results. Operability of sensitive equipment vital for plant safety may be lost due to heavy vibrations resulting from impact load.

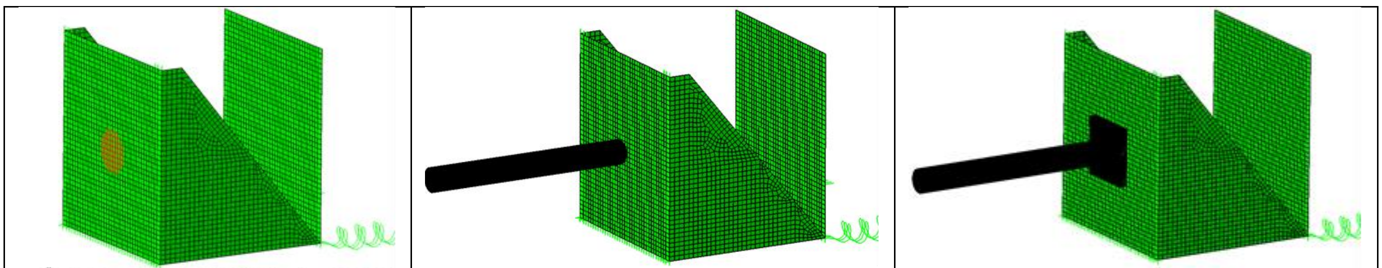
Vibration propagation test series V, which is a part of an experimental programme conducted at VTT concerning impact loaded concrete structures, was initiated with a test called V0, Vepsä et al. (2015). Test structure V0 was supported with a steel frame in a similar way as in the slab specific tests earlier in related test series. Based on experience with test V0 the next test structure V1 was designed so that the use of supporting frame could be avoided. In this way, damping effect would remain as much as practically possible in the V1 structure itself. The specimen rests on elastomeric bearing pads and it is additionally supported in the horizontal and vertical directions. The reinforced concrete test structure is described in more detail in Saarenheimo et al. (2017).

Damping is an important factor influencing the response of structures subjected to impact and especially when studying the propagation of vibrations in concrete structures. Some guidelines for selecting damping values for reinforced concrete structure under different conditions can be found in literature. In Reference Stevenson (1980), in Table 4, a damping value of 2% from the critical damping value (corresponding to damping ratio of 0.02) is given for concrete with slight cracking and with reinforcement below yield point. With considerable cracking the damping ratio increases to 0.03-0.05. At yield point the damping ratio becomes still higher, about 0.07-0.1 and beyond yield point even higher. More recent studies on damping in concrete structures are reported e.g. in References Chowdhury (1999) and Saltzmann (2002).

The vibration propagation and damping test V1A is studied with several alternative modelling assumptions in order to find out how good agreement can be obtained in different independent analyses. Rayleigh damping model, Chopra (1995), is used for simplicity.

CALCULATION MODELS

FE models



Shell LF	Shell M	Solid M

Figure 1. Finite element models ‘Shell LF’ and ‘Solid M’ by Abaqus.

Accuracy and capabilities of different types of modelling assumptions are studied by simulating the vibration test V1A using three different types of finite element (FE) models, Abaqus (2014). The simplest one is a shell element model of the reinforced concrete mock-up loaded with an analytically defined loading function. The loading area is indicated on the front surface of the shell element model shown on the left hand side in Figure 1. The width of the structure is 2.0 m and the span width of the front wall is 0.185 m. The thickness of the front wall, the triangular shaped side walls and the floor slab is 0.15 m and the thickness of the rear wall is 0.25m. Nonlinear behaviour of concrete was modelled by using the concrete damage plasticity model. In these studies the fracture energy was assumed to be 100 J/m^2 and tensile strength after cracking was assumed to decrease bi-linearly. This FE model, referred to as ‘Shell LF’, the loading function defined by the Riera method, Riera (1968), and test arrangements of the vibration test V1A are presented in Saarenheimo et al. (2017).

In the next phase the shell element structural model was impacted with a FE model of the missile. The stainless steel missile was modelled with shell elements and the measured impact velocity, 113.6 m/s, was set as an initial velocity. This calculation model is referred to as ‘Shell M’.

Further, a part of the front wall comprising the hit area and its neighbourhood was modelled with eight noded solid elements. The bending reinforcement bars were modelled with beam elements. In order to study the effect of confinement behaviour and strain rate dependency of concrete material properties, also material input data obtained by applying the method presented in Fedoroff (2017) was applied. This methodology enables also deletion of elements. The assumed value of the static tensile strength was 2.63 MPa and the corresponding tensile fracture energy was 100 J/m^2 for all these three calculation models.

FE model, referred to as ‘Solid M’, of the structure and the missile model is shown on the right hand side in Figure 1. The total length of the missile is 2286 mm. The diameter of the cylindrical pipe is 245 mm and the wall thickness of the pipe is 2 mm. The thickness of the front cap is 3 mm. By adding some steel parts at the rear end of the missile the total mass increases to 50 kg. In order to model the folding deformation of the missile due to impact, the element mesh should be rather dense. The average element size in the missile shell element model is 5 mm and the number of four-noded shell elements with one point reduced integration is over 70000. Nonlinear material properties of stainless steel were taken into consideration using an elastic plastic material model with isotropic yield hardening and the von Mises yield condition.

The number of four noded elements in the shell element calculation model of the reinforced concrete mock-up is about 5800 and the corresponding number of degrees of freedom (DOF) is 35 500. By using the missile model as an impactor the number of DOF becomes 466 000 and when the solid elements are used at the impact area, the amount of DOF is 588 000. A Rayleigh damping of 5% at the frequencies of 45 Hz and 5000 Hz was assumed in these studies. Geometric nonlinearity is taken into consideration is these analyses.

RESULTS

Effect of modelling technique

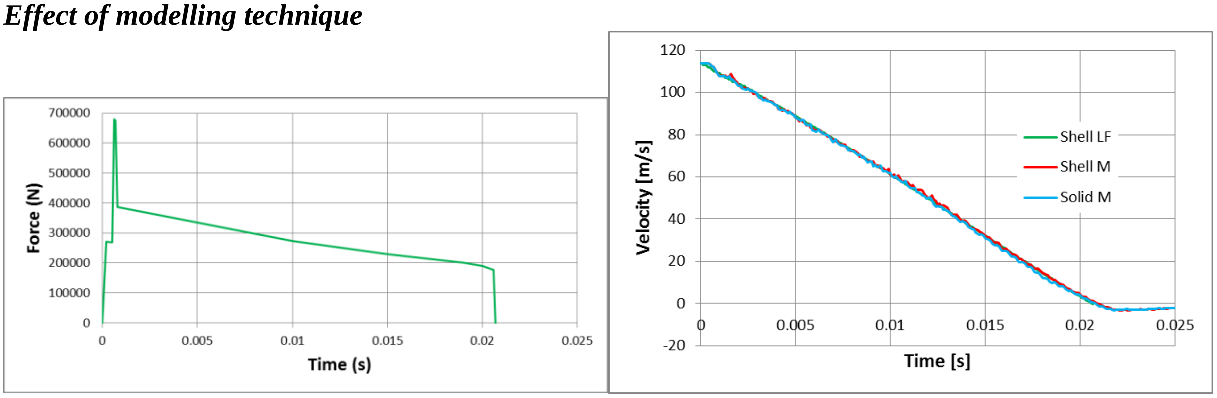


Figure 2. Force-time function and velocity of the missile during the impact.

The load function calculated by the Riera method is presented in Figure 2 on the left. The decreasing velocity of the missile during the impact based on finite element simulations and the Riera method are presented in Figure 2 on the right hand side. According to all these three approaches, the numerically predicted impact duration was 21 ms. The corresponding estimated impact duration in the test was 19 ms. The deformed missile and the corresponding deformed FE model are presented in Figure 3. The total shortening of the missile during the test was about 1.02 m, the length of the folded part was about 20 cm and the remaining length of the straight part was 1.09 m. According to the finite element simulation, the shortening is 1.22 m. Based on the results obtained by the Riera method, the length of the straight part after the impact is 1.09 m. When the length of the folded part is added to the shortening, it is comparable to the shortening given by the Riera method.

Figure 3. Deformed missile.

Measured and calculated deflections at the impact point are presented as a function of time in Figure 4. The maximum deflection obtained by using the FE model of the missile to generate loading and shell element model for the structure (Shell M) is clearly higher than the corresponding result obtained with the two other models and also the permanent deflection is somewhat overpredicted. The permanent deflection is well predicted with the two other models using different types of loading assumptions (Shell LF and Solid M). Horizontal displacements at the top of the rear wall are presented in Figure 5. Bending vibration behaviour is not well predicted by any of these models. One reason for that may be the horizontal support arrangement, that was difficult to model at the lower corners of the rear wall.

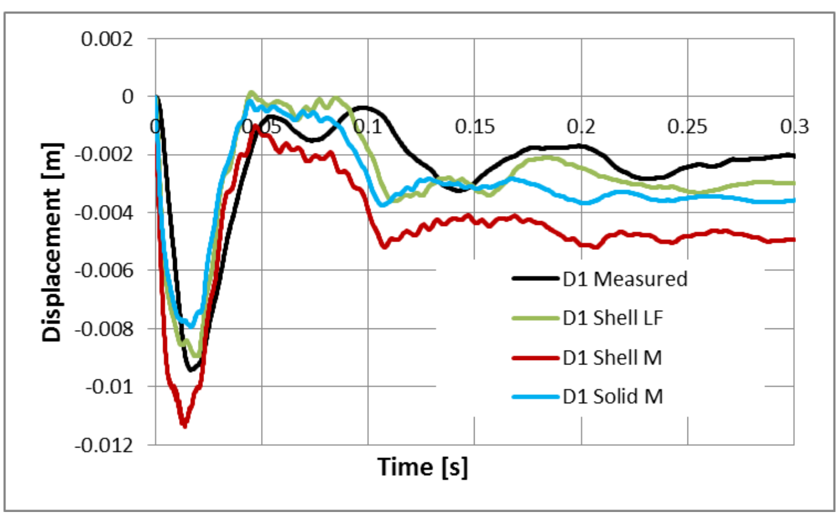


Figure 4. Horizontal displacement at impact point as a function of time.

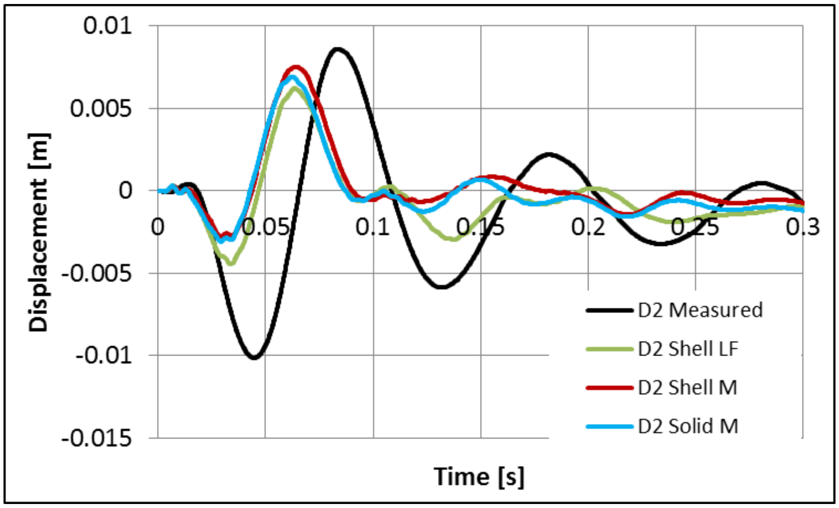


Figure 5. Horizontal displacement at the top of the rear wall as a function of time.

Floor response spectra were computed from the measured and calculated acceleration results adopting a 5% damping. All the accelerometers were located at vertical symmetry plane of the structure. Locations of accelerometers are presented in Saarenheimo et al. (2017). Calculated displacement and acceleration spectra results are compared with the corresponding measured values. Vertical displacement spectra obtained in the middle of the floor slab (point A2) are presented in Figure 6 on the left hand side and the corresponding acceleration spectra are shown on the right hand side. Displacement and acceleration spectra at the floor slab rear wall junction (point A3) are depicted in Figure 7. Vertical displacement and acceleration spectra results at the rear wall, in the middle of the height (point A4) are shown in Figure 8 and at the top (point A5) are shown in Figure 9. Horizontal displacement and acceleration spectra at the same locations in the rear wall are presented in Figure 10 (point A4) and in Figure 11 (point A5). All the presented displacement spectra values at frequencies over 50 Hz are less than 2 mm and thus also the acceleration spectra in the frequency range over 50 Hz are of minor importance.

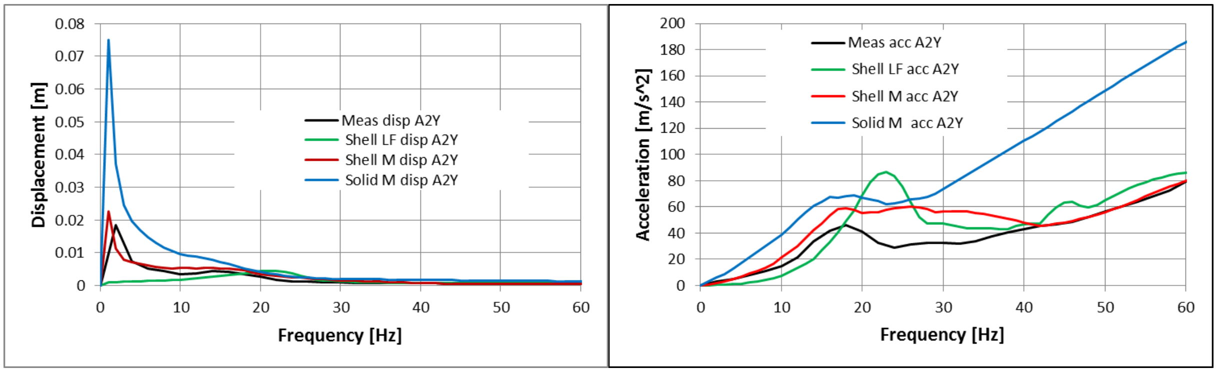


Figure 6. Displacement and acceleration spectra in the middle of the floor, vertical direction.

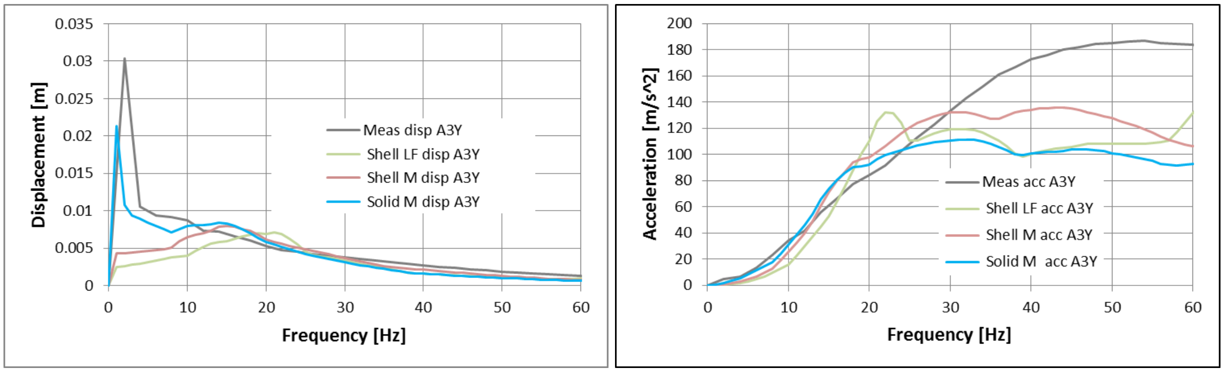


Figure 7. Displacement and acceleration spectra at the floor slab rear wall junction, vertical direction.

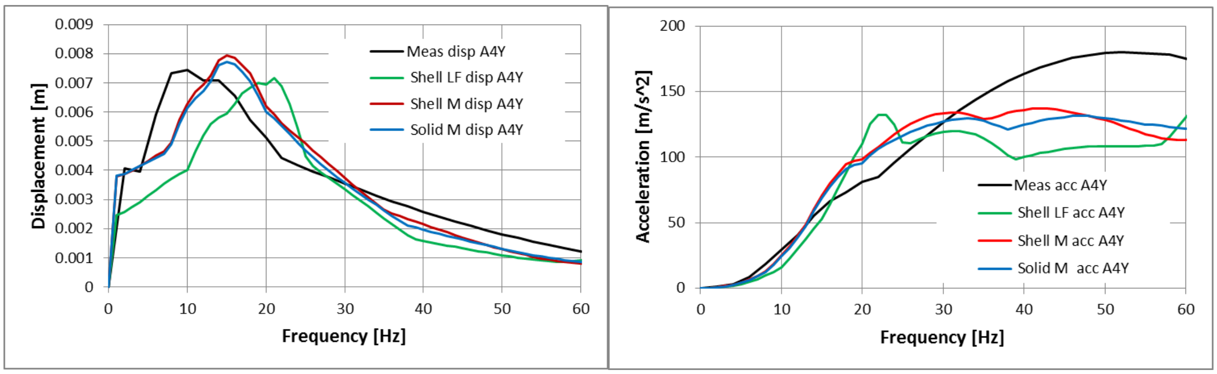


Figure 8. Displacement and acceleration spectra at the middle of the rear wall, vertical direction.

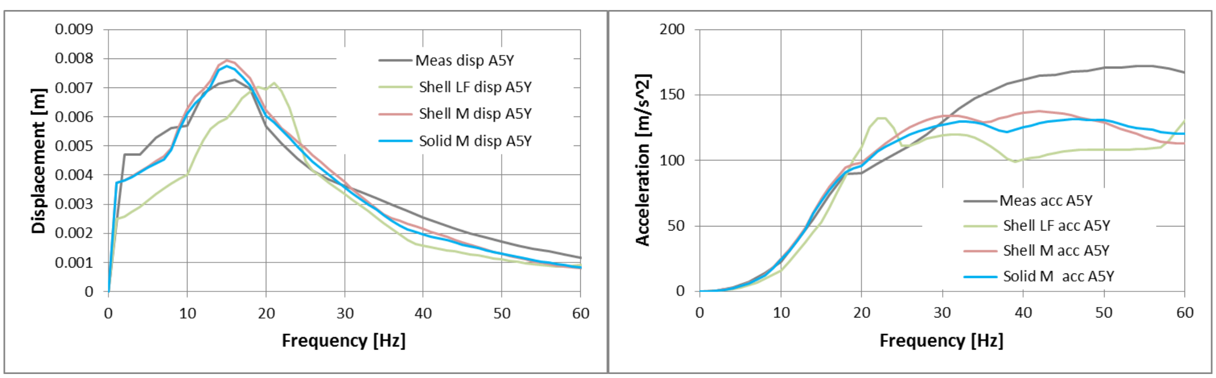


Figure 9. Displacement and acceleration spectra at the top of the rear wall, vertical direction.

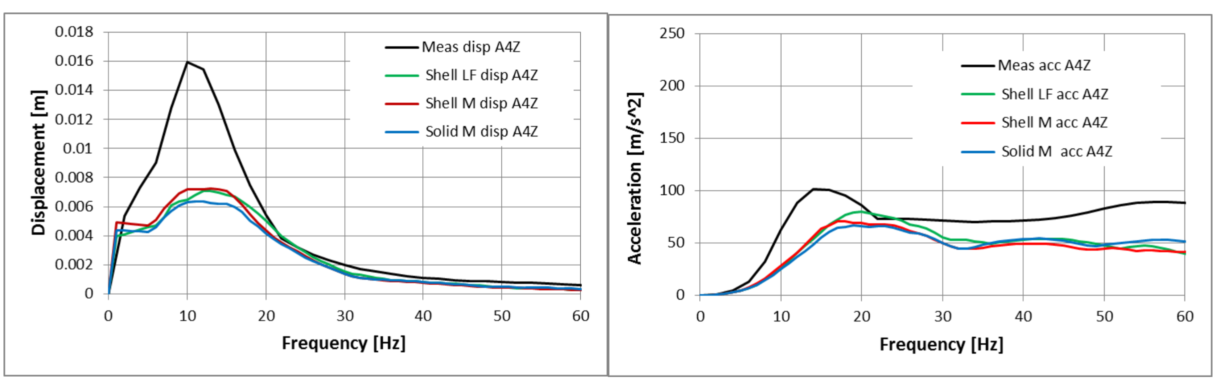


Figure 10. Displacement and acceleration spectra at the middle of the rear wall, horizontal direction.

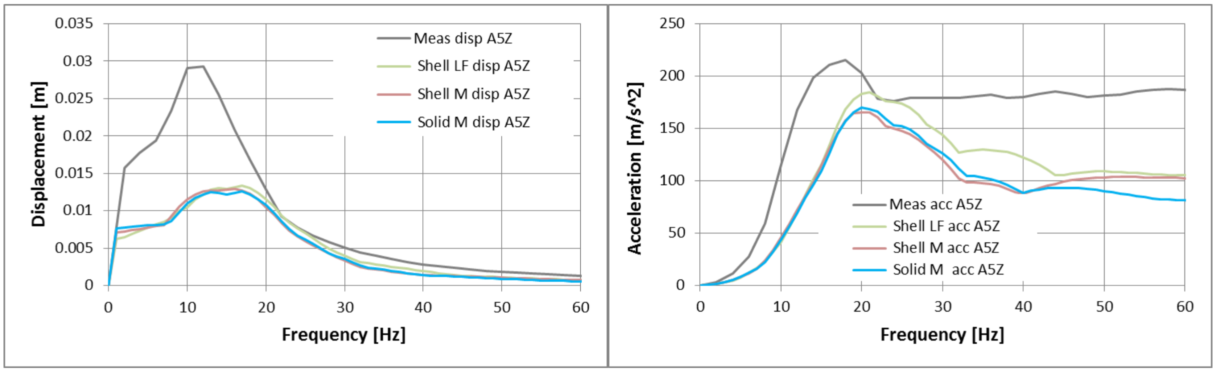


Figure 11. Displacement and acceleration spectra at the top of the rear wall, horizontal direction.

At lower frequencies the vertical acceleration spectra and also displacement spectra obtained by using the loading function are lower than the corresponding spectra obtained by using the combined missile/structure model. At higher frequencies (over 20 Hz) the horizontal acceleration spectra values are higher when the loading function is applied.

Effect of damping

The shell element model loaded by the analytically defined loading function (Shell LF) was used for sensitivity studies on damping properties. Rayleigh damping model, Chopra (1995), was used. Damping assumptions used in these sensitivity studies are presented in Figure 12. These analyses were carried out as geometrically linear. Calculated horizontal displacements as a function of time at the impact location are presented with the corresponding measured curve in Figure 13. The maximum deflection and the permanent displacement are predicted quite well with all the applied damping assumptions. Horizontal displacements at the top of the rear wall are shown in Figure 14 and vertical displacements of the rear wall are presented in Figure 15. Calculated bending vibration at the top of the rear wall is, of course, dependent on the assumed damping. But even with the lowest damping assumption applied here, the bending vibration of the rear wall was not captured well. The horizontal support arrangement at the lower corners of the rear wall may have an effect on the results due to uncertainties in modelling details.

Vertical acceleration spectra in the middle of the floor and at the floor and rear wall junction are shown in Figure 16. Horizontal acceleration spectra at the back wall are presented in Figure 17. In the frequency range below 15 Hz the vertical acceleration responses are quite well predicted with all the applied damping assumptions. Horizontal acceleration spectra at the rear wall are accurately predicted at the frequencies below 12 Hz with the lowest damping assumption.

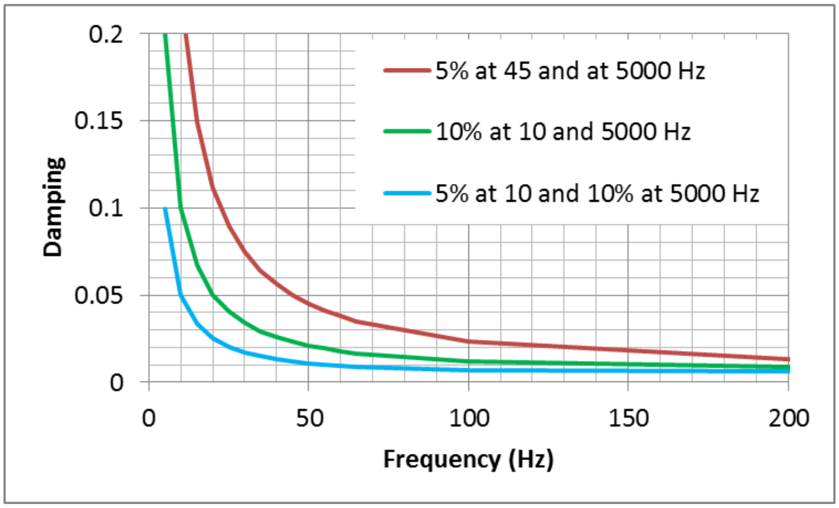


Figure 12. Damping assumptions.

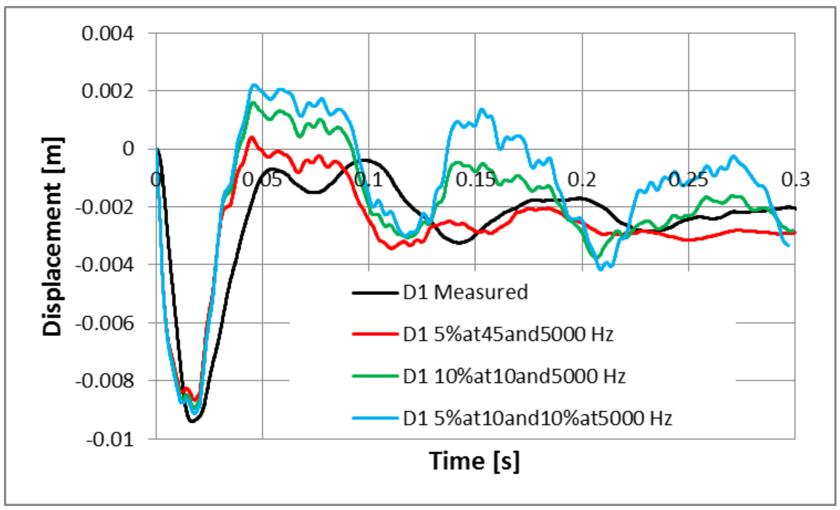


Figure 13. Horizontal displacement at impact point as a function of time.

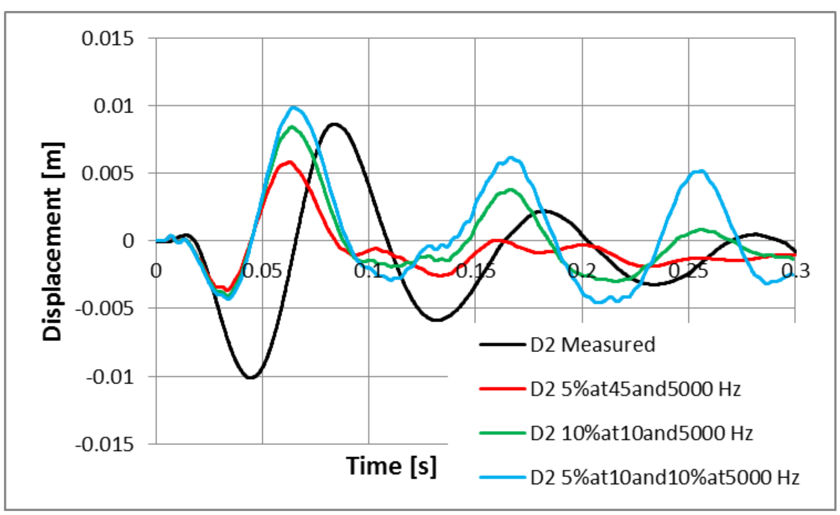


Figure 14. Horizontal displacement at the top of the rear wall as a function of time.

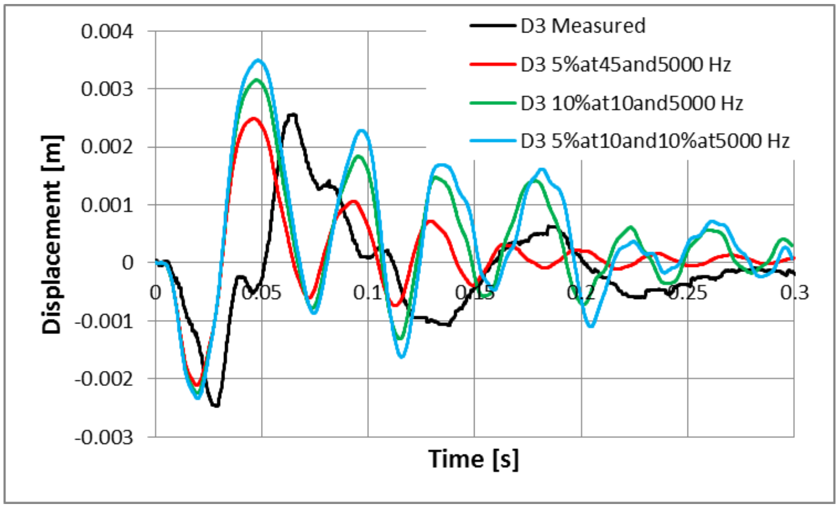


Figure 15. Vertical displacement of the rear wall as a function of time.

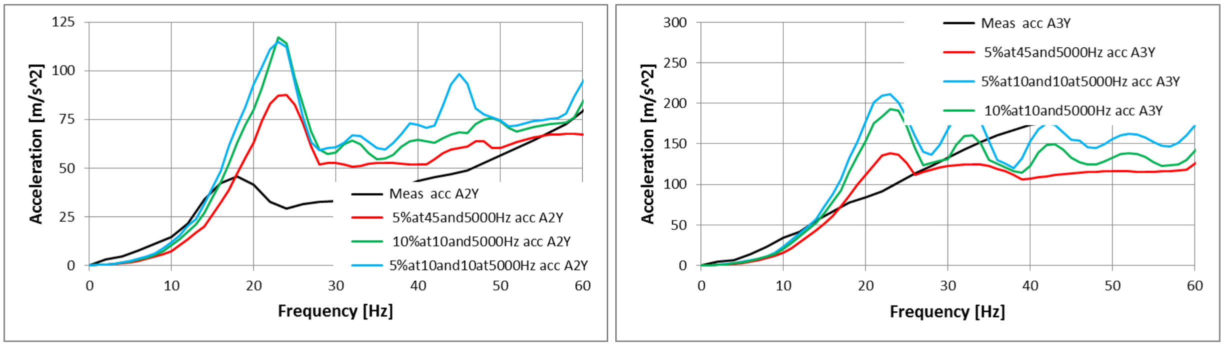


Figure 16. Acceleration spectra in the middle of the floor and at the floor rear wall junction, vertical direction.

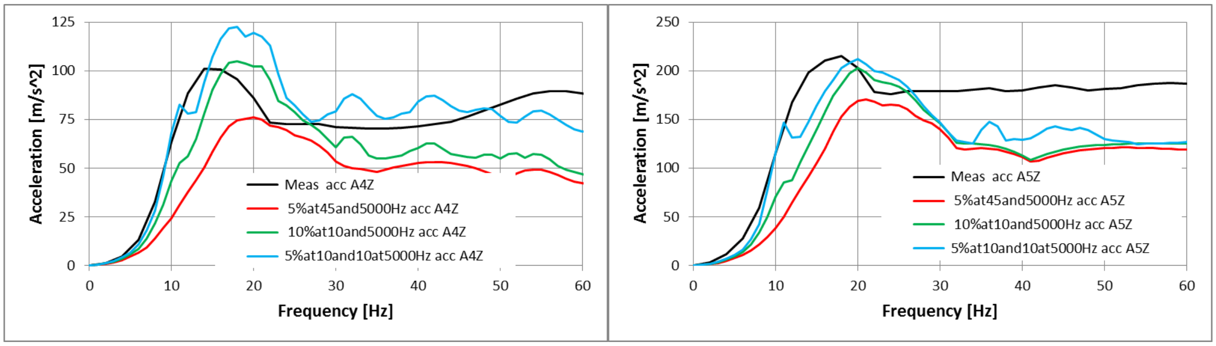


Figure 17. Acceleration spectra at the middle and top of the rear wall, horizontal direction.

CONCLUSION

Calculated displacement behaviour results are somewhat dependent on the applied modelling technique. The largest maximum and permanent displacements were obtained by using the shell elements model loaded by the FE model of the missile. Effect of modelling technique on the acceleration spectra results is not evident. It cannot be clearly stated that one of these approaches gives a conservative result.

Assumed damping is not affecting much the maximum deflection value at the hit point. Also, the permanent deflection obtained with different damping assumptions used here is quite similar.

Displacement spectra results in the frequency range over 50 Hz are less than 2 mm and thus of minor importance. Acceleration response spectra were best predicted using the lowest assumption for damping. It should be noted that the Rayleigh damping approach was used in these sensitivity studies for its simplicity. It is not a physically correct way to take damping into consideration in this type of analyses.

REFERENCES

Abaqus Theory Manual. (2014). Version 6.14-1. Dassault Systémes.

Chopra, A.K. (1995). Dynamics of Structures, fourth ed. Prentice Hall. London.

Chowdhury, S.H. (1999). Damping characteristics of reinforced and partially pre-stressed concrete beams. Griffith University.

Fedoroff, A., Kuutti, J. and Saarenheimo, A. (2017). ”A physically motivated element deletion criterion for the concrete damage plasticity model”, *Transactions, SMiRT-24,* Division III.

Riera, J.D. (1968). “On the stress analysis of structures subjected to aircraft impact forces”. *Nuclear Engineering and Design*, 8, 415–426.

Saarenheimo, A., Calonius, K., Fedoroff, A., Tuomala, M. and Vepsä, A. (2017). ”Experimental and numerical studies on vibration propagation”. *Transactions, SMiRT-24,* Division V.

Saltzmann, A. (2002). “Damping characteristics of reinforced and prestressed normal and high-strength concrete beams”. PhD thesis, Griffith University.

Stevenson, J. D.(1980). “Structural Damping Values as a Function of Dynamic Response Stress and Deformation Levels”, *Nuclear Engineering and Design* **60** 2 (1980) 211-237.

Vepsä, A., Aatola, S., Calonius, K. and Halonen, M. (2015). “Impact testing of a wall-floor-wall reinforced concrete structure”. Transactions, SMiRT-23 Manchester, United Kingdom - August 10-14, 2015, Division V, Paper ID 337.