Analysis of vibration propagation and damping tests of reinforced concrete structures within IMPACT III Project

Christian Schneeberger\textsuperscript{1}, Michael Borgerhoff\textsuperscript{2}, Friedhelm Stangenberg\textsuperscript{2}, Rainer Zinn\textsuperscript{2}

\textsuperscript{1}Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland
\textsuperscript{2}Stangenberg & Partner Ingenieur-GmbH, Bochum, Germany

email: christian.schneeberger@ensi.ch, borgerhoff@stangenberg.de, stangenberg@stangenberg.de, zinn@stangenberg.de

ABSTRACT: This paper focuses on outcomes of a collaborative work between the Swiss Federal Nuclear Safety Inspectorate ENSI and its consultant Stangenberg & Partner. ENSI participates in the IMPACT III project organized by the VTT Technical Research Center of Finland and funded by several institutions including ENSI. As part of the IMPACT III project, reduced scale impact tests of reinforced concrete slabs and structures are being carried out in Espoo (Finland). The series of vibration propagation and damping tests pursues the objective of investigating the influence of non-linear structural behaviour on the induced vibrations of reinforced concrete structures and their damping. The planning and simulation of the vibration propagation and damping test V1 is presented; in the oral presentation of the paper, the results will be compared with those obtained in the test which will be carried out in spring, 2014. The general object of the exercise is to improve the safety of nuclear facilities and, more specifically, to demonstrate the capabilities of current finite element techniques to simulate the vibration propagation through a reinforced concrete structure, which is subjected to non-linear deformations by the impact of a soft missile.

KEY WORDS: Impact; Aircraft impact; Reinforced concrete; Tests; Non-linear computations; Induced vibrations; Damping.

1 INTRODUCTION

In the frame of the program IMPACT, impact tests with reduced scale targets are carried out at the Technical Research Center VTT in Espoo (Finland), cf. Vepsä et al. [4]. The tested reinforced concrete walls up to now are approx. 2.1 m square slabs, which are simply supported at each side with the span width of 2.0 m. The slabs are fixed by a steel frame, which is supported by four steel backpipes, see Figure 1.

Figure 1. Test wall with steel frame.

Within the first two phases of this program, the objective of the tests with deformable (soft) missiles was to study the global, bending behaviour of 0.15 m thick walls. Walls with 0.25 m thickness have been used for studying the local, punching behaviour caused by impacts of hard missiles. In a third phase of the program (IMPACT III), since 2012 also combined bending and punching tests are included. The objective of these tests is to investigate the influence of combinations of longitudinal and transverse reinforcement on the structural behaviour while almost reaching the ultimate load capacity of the slab in bending and shear. A new test series is now introduced referring to the propagation of vibrations and to damping in r/c structures; their design and blind pre-computations are described in this paper.

2 EXISTING TEST EQUIPMENT AND PARAMETERS

The tests are carried out in the VTT Technical Research Centre of Finland in Espoo. Figure 2 shows a photo of the test facility with a 13.5 m long pressure vessel in the rear part (in the foreground of the photo) and a 12 m long tube, in which the projectile can be accelerated up to 200 m/s. The maximum projectile mass is 100 kg; when using a 50 kg projectile, the maximum impact velocity is limited to approx. 165 m/s.

Figure 2. Test equipment at VTT in Espoo (Finland).
The deformable missiles consist of a stainless steel pipe with a convex end cap in front and a flat carbon steel plate at the end. As an example, the crumpled shape of the projectile of force plate test FP5 is shown in Figure 3. It has been shortened by the impact with 155 m/s from originally 1.5 m to 0.65 m residual length.

Figure 3. Soft projectile after test

3 NEW VIBRATION PROPAGATION TESTS

The objective of the vibration propagation and damping tests is to investigate the influence of non-linear structural behaviour on the induced vibrations of reinforced concrete structures subjected to impact and their damping. The structural design of the test specimen underlies the principal idea to simulate the path of vibrations travelling from the impact location on the building through the baseplate up to the position of the accelerated component to be verified (i.e. due to aircraft crash on a reactor building, see Figure 4).

Figure 4. Principal idea for an induced vibration test.

This concept is fulfilled on principle by the test configuration shown in Figure 5. The test structure with the external dimensions of a cube with 2.0 m side length consists of a vertical impact wall, a connecting floor and a rear wall. The structural parts are designed to experience non-linear steel and concrete strains only in the immediate impact zone of the front wall. The deformation behaviour of the other structural parts is expected to be linear.

Figure 5. General vibration test configuration.

The test structure has to be equipped with an instrumentation consisting of load cells for measurement of the support forces, strain gauges for the purpose of checking the material behaviour, displacement sensors and accelerometers for recording the vibration behaviour.

4 DESIGN AND NUMERICAL RESULTS

4.1 Specimen of vibration test V1

The structure for the first vibration propagation and damping test according to the principal idea illustrated in Figure 5 was configured with a vertical impact wall, a connecting floor and a rear wall, see Figure 6 and Figure 7. Additionally, two triangular side walls are arranged for strengthening the impact wall and the floor slab. The structure is simply supported in horizontal direction at the rear end of the floor to prevent sliding and in vertical direction at the top of the front wall to prevent lift off. The structure rests on 0.15 m and 0.25 m wide strips of rubber at the front and rear edges of the floor respectively. The overall size of the structure is 2.0 m in all orthogonal directions with wall thicknesses 0.15 m for front and side walls as well as floor slab, and 0.25 m for the rear wall. The design of the structure and the missile parameters are chosen in order to limit non-linear behaviour on the impact zone of the front wall.

Figure 6. Side view of specimen for test V1.
The concrete quality of the specimen is C40/50. The reinforcement is made of steel with yield strength 500 MPa. Larger amounts of reinforcement are arranged in the corners of the floor slab and the connected walls in order to prevent plastic deformations. Transverse reinforcement made by closed stirrups $\Phi 6$ mm c/c 100/100 mm is arranged in a central area of the front wall 0.8 m wide and 0.8 m high.

4.2 Numerical Model

The verification analyses have been performed with a Finite Element (FE) model of the specimen by use of the computer program SOFiSTiK; cf. SOFiSTiK AG [3]. The model is depicted in Figure 8 and Figure 9, respectively. The concrete floor slab and the walls are modelled by shell elements. Each elastomer strip bearing is represented by one row of spring elements transferring compression forces exclusively. The vertical supports of the front wall are represented by spring elements, which only are able to transfer compression forces, too. The horizontal supports are capable to transfer tension as well as compression forces.

4.3 Impact Characteristics

The 2261 mm long missile is constituted by a stainless steel tube with diameter 254 mm and shell thickness 2 mm with a front cap with shell thickness 3 mm and a 25 mm thick carbon steel end plate. The total missile mass is 50 kg.

Based on these data, a load-duration of 18 ms was predicted in blind FE pre-computations of a missile impacting on a rigid target with an impact velocity of 110 m/s, see Figure 10. In a complementary analysis, the impact velocity 160 m/s is investigated as upper limit. The smoothed load functions derived by the Riera method for 110 m/s and 160 m/s are shown in Figure 10, too. The missile is of same type as used in the bending test described in [5]; as demonstrated there, the results derived from Riera method and FEM loads are both close to the measured results for impact velocity 110 m/s.

4.4 Numerical Analyses

The program used for the non-linear dynamic FE analyses is SOFiSTiK; cf. SOFiSTiK AG [3]. The analysis of non-linear effects in SOFiSTiK is done by iterations using a modified Newton method; i.e. an implicit integration scheme is used.
The calculation code SOFiSTiK is well-suited for the analysis of r/c targets subjected to extreme impact loads, cf. Chauvel et al. [1], Zinn et al. [2], and Borgerhoff et al. ([5] and [6]). In the SOFiSTiK code, the reinforced concrete target is modelled with non-linear, layered shell elements; non-linear shear deformations of shell/plate elements are approximately included. The non-linear material behaviour of reinforced concrete in the shell elements is regarded by use of a layer model with arrangement of the crosswise arranged layers of bending reinforcement in their correct positions near the surfaces. The non-linear behaviour of the components of reinforced concrete is defined by

- non-linear uniaxial stress-strain laws of concrete including hysteretic behaviour as shown for concrete in compression in Figure 11 (including increase in strength due to biaxial compressive behaviour),
- consideration of tension softening of concrete after cracking dependent on fracture energy with hysteretic behaviour as shown in Figure 12,
- approximate inclusion of transverse shear deformations by an elastic/ideally plastic shear stress/shear strain law after exceeding the specified ultimate shear strength as shown in Figure 13, and
- tri-linear stress-strain laws of reinforcing steel with hysteretic behaviour as shown in Figure 14.

By use of the layer model implemented in SOFiSTiK, the shell element is divided into a specified number of layers. A partition into 12 layers is sufficient according to our experience and is used in the performed analyses. At each layer surface, the principle stresses are calculated. Dependent on the ratio of the two principle stresses in each principle stress direction, a fictitious uniaxial stress-strain law regarding the biaxial behaviour is derived. The non-linear stresses gained by that procedure are integrated over all layers into resulting forces and moments. Subsequently, the reinforcement forces including the tension stiffening effect are added.

A specific type of unreinforced elastomeric bearing has been chosen to define the spring stiffness of the elastomer strip bearings. The effect that the dynamic spring stiffness of the elastomeric bearing is larger than the static spring stiffness has been neglected.

Damping is introduced by means of Rayleigh damping parameters $\alpha$ and $\beta$ which are defining the damping matrix. The Rayleigh damping parameters for the r/c elements are introduced in a way that the damping ratios at 8 Hz and 50 Hz are 1 % of critical damping. Hence follow the Rayleigh parameters $\alpha = 0.866645$ and $\beta = 0.000055$. The low damping of 1 % is supposed since non-linear computations already comprise damping effects. This is a conservative assumption for the rear wall, because its behaviour remains linear.

The degree of damping of the chosen bearing is $D = 8 \%$. The corresponding Rayleigh parameter in the step-by-step integration computations is $\beta = D / (\pi \cdot f)$, which results in $\beta = 0.001135$ for the decisive frequency $f = 22.44$ Hz.

From the linear-elastic eigenmodes, the 6th mode is shown in Figure 15 as first bending mode of the front wall.
Figure 15. 6th eigenmode of linear-elastic system, frequency 74.7 Hz.

The analyses of the FE model shown in Figure 8 and in Figure 9 have been performed for impact velocities $v = 110 \text{ m/s}$ and $v = 160 \text{ m/s}$ by use of the load functions according to Figure 10. Subsequently, selected analysis results are documented on the basis of plots of the maximum steel strains and concrete compression strains during the investigated time period.

In Figure 16 and Figure 17, the maximum steel and concrete strains of the front wall are depicted for $v = 110 \text{ m/s}$. Non-linear steel and concrete strains are limited to the impact zone in this case.

Figure 16. Maximum steel strains of the front wall in \% for $v = 110 \text{ m/s}$.

Figure 17. Minimum concrete strains of the front wall in \% for $v = 110 \text{ m/s}$.

In Figure 18 and Figure 19, the results for $v = 160 \text{ m/s}$ are depicted for comparison. Non-linear steel and concrete strains do not remain limited to the proximate impact zone. The maximum steel strains at the upper edge of the front wall at a later time reach the ultimate elongation of the reinforcing steel. The minimum concrete strains in the impact zone indicate that no residual concrete strength has remained and distinct scabbing occurs. In the other structural parts moderate non-linear behaviour is limited to small areas.

Figure 18. Maximum steel strains of the front wall in \% for $v = 160 \text{ m/s}$.
Figure 19. Minimum concrete strains of the front wall in % for $v = 160$ m/s.

In case of impact velocity 160 m/s, the large non-linear strains near structural failure and the calculated large lift-off at the rear wall are considered as disadvantageous for the objectives of test V1. Therefore, the execution with $v = 110$ m/s was recommended preferably.

As further results of the computations performed for this impact velocity,

- selected displacements,
- the horizontal support forces at the rear end of the floor slab,
- the support forces acting on the vertical bearings at the upper side of the front wall, and
- the accelerations of the rear wall

are presented in terms of time history diagrams. Based on the acceleration time histories, the corresponding response spectra have been derived.

The diagrams in Figure 20 and Figure 21 show a comparison of the displacements computed for the load-time functions derived by Riera method as well as calculated by FE analysis. More pronounced than observed in calculations for the flat slabs of the former program phases, the oscillating FEM load function leads to larger displacements than the Riera load function. But this behaviour especially becomes effective when the rear wall is swinging back.

Figure 20. Horizontal displacements for $v = 110$ m/s (load-time functions as shown in Figure 10).

Figure 21. Vertical displacements for $v = 110$ m/s (load-time functions as shown in Figure 10).

Figure 22 and Figure 23 show the time histories of the horizontal and vertical support forces (supports as shown schematically in Figure 6 and Figure 7; forces refer to one of the two supports each).

Figure 22. Horizontal support forces for $v = 110$ m/s (Riera load function).
Figure 23. Vertical support forces of the front wall for \( v = 110 \text{ m/s} \) (Riera load function).

Figure 24 through Figure 26 show the expected horizontal acceleration time histories at mid of top and bottom of the rear wall computed for the load-time functions as represented in Figure 10.

The corresponding response spectra for 5% damping have been determined for both locations as well as the three load functions and are depicted in Figure 27 and Figure 28.
The response spectra for the load functions derived by Riera method and FEM method are similar until approximately 300 Hz and only differ significantly above this frequency. It can also be observed, that there is a frequency drop of the linear frequency 74.7 Hz to ~64 Hz in case of 160 m/s impact velocity.

5 CONCLUSIONS

The objective of the vibration propagation and damping tests in the frame of the program IMPACT III is to investigate the influence of non-linear structural behaviour on the induced vibrations of reinforced concrete structures subjected to impact and their damping. The test structure with the external dimensions of a cube with 2.0 m side length consists of a vertical impact wall, a connecting floor and a rear wall. The structural parts are designed to experience non-linear steel and concrete strains only in the immediate impact zone of the front wall.

The description of the pre-calculations in this paper has been concentrated on the impact velocity $v = 110$ m/s, which is recommended for the first vibration test V1. The non-linear FE computations of the test structure have been performed by use of two different load-time functions, one of them calculated by FE computations of a missile impacting on a rigid target and another smoothed one derived by the Riera method.

More pronounced than observed in calculations for the flat slabs of the former program phases, the oscillating FEM load function leads to larger displacements than the Riera load function. The response spectra for the load functions derived by Riera method and FEM method are similar until approximately 300 Hz and only differ significantly above this frequency. The results of the pre-calculations will be compared with those obtained in the test, which is planned to be carried out in spring 2014, in the oral presentation of the paper.

REFERENCES