Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division 05

BENDING DAMAGE OF REINFORCED CONCRETE SLABS SUBJECTED TO SOFT MISSILE IMPACT: NUMERICAL SIMULATION OF INCLINED IMPACTS

Sara Ghadimi Khasraghy[1], Bastian Wilding[2], Christian Schneeberger[3], Michael Borgerhoff[4], Matthias Stadler[5], Peter Zwicky[6]

[1,2,6] Basler & Hofmann AG, Consulting Engineers, Zurich, Switzerland, Sara.Ghadimi@baslerhofmann.ch
[3] Deputy Section Head, Civil Engineering Section, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland
[4,5] Stangenberg & Partners Consulting Engineers, Bochum, Germany

ABSTRACT

The fourth phase of the IMPACT project, organized by VTT Technical Research Centre in Espoo (Finland), was launched in 2019. The project IMPACT IV – NEREID (**NE**w **R**esearch **E**ffort in the **I**mpact **D**omain), focuses on the influence of the test scaling on the various structural response phenomena studied in the previous three phases of the IMPACT project, as well as on obtaining further experimental data exploring new scenarios of impact loading on reinforced concrete structures.

The project IMPACT IV – NEREID includes a series of so-called IB (inclined bending) tests with inclined reinforced concrete slabs subjected to impacts of deformable missiles. The IB tests have the objective to investigate the effect of target inclination on the flexural response of the reinforced concrete slabs, as well as sliding and the rotational response of the missiles.

The capability of numerical analyses to replicate the impact response of inclined reinforced concrete slabs is explored using two different finite element software programs (LS-DYNA and SOFiSTiK). The analyses predicted the overall response of the inclined slabs well. For the implicit analyses, using SOFiSTiK, the loading (force time history) has to be predefined. The explicit analyses using LS-DYNA, on the other hand, have the advantage of simulating the interaction between the missiles and the slabs, in which the sliding and rotation of the missiles and a possible tail hit can be simulated if a correct coefficient of friction is assumed between the projectile and the target.

INTRODUCTION

The IMPACT project started in 2003 by VTT and STUK (Finnish radiation and nuclear safety authority). Foreign partners joined the project in the follow-up phases IMPACT I – III (2006 – 2018). VTT continues to organize the fourth project phase (IMPACT IV – NEREID), which is funded by several institutions including the Swiss Nuclear Safety Inspectorate (ENSI).

The IMPACT project aims at performing experimental and numerical studies of impact loading on reinforced concrete structures. In order to validate the test results from the previous IMPACT phases, the test scaling effects, as well as new impact scenarios are studied. This paper investigates the influence of slab inclination on the flexural response of the reinforced concrete slabs, as well as sliding and the rotational response of the missiles.

The contribution of the ENSI and its consultants Basler and Hofmann AG (B&H), as well as Stangenberg and Partners (SPI) in numerical simulation of IB tests carried out as a part of the IMPACT IV – NEREID project is outlined here.

EXPERIMENTS

Four reinforced concrete square-shaped (2.1 m × 2.1 m) slabs, tests IB1 – 4, are used to study inclined impact on the slabs under soft impact of 50 kg missiles as outlined in Table 1. Additionally, a force plate test on a rigid target was performed. These experiments were carried out at VTT in 2020 (Fedoroff 2021). The soft impact tests TF11 and TF12 carried out in the second phase of the project IMPACT II (Vepsä et al. 2013 and Tarallo et al. 2013) were chosen as reference tests for the IB series.

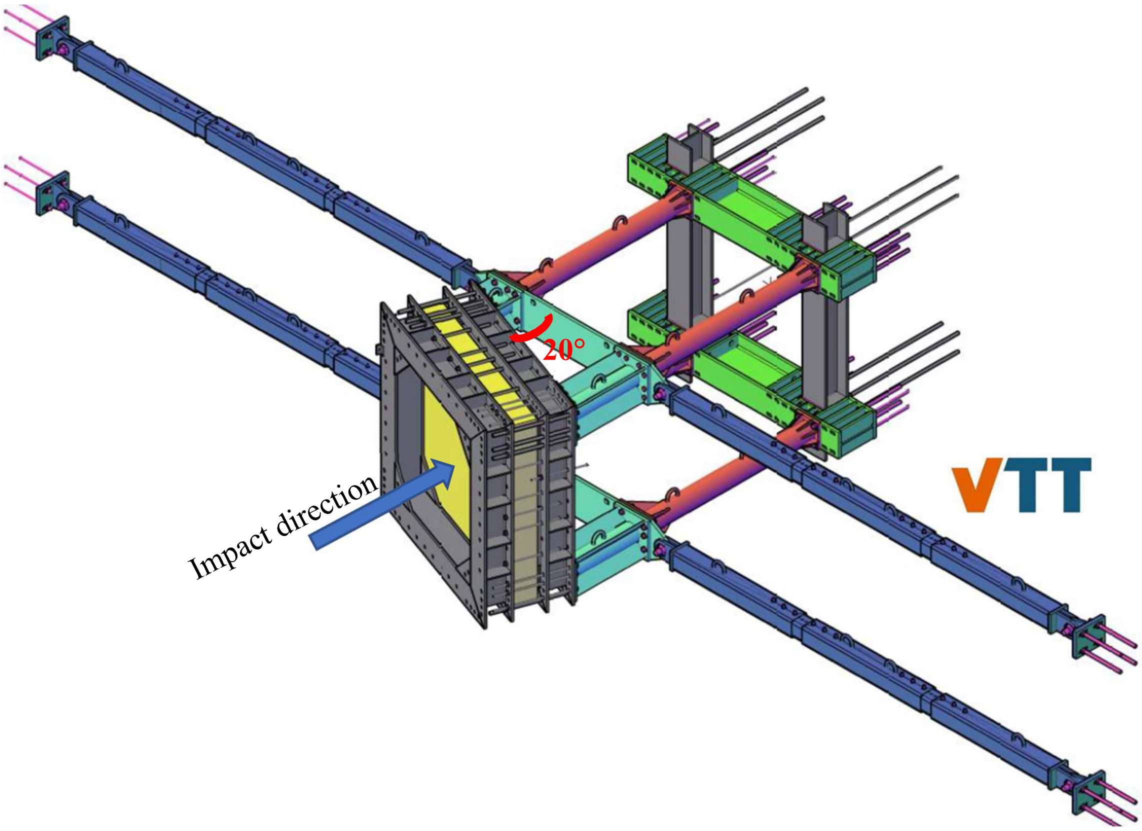

Figure 1. Test setup for an inclination angle of 20° (Fedoroff 2021)

The force plate test FPI1 was performed first with the impact velocity of 114.5 m/s on a steel plate inclined by 20°. This test served to study the loading characteristic and behaviour of the missile. The missile slid away laterally causing a rotation and a subsequent impact of the missile tail, which is a 25 mm thick and 10 kg heavy steel plate located at the projectile end. Based on the outcome of the force plate test, additional measures were taken for the IB tests in order to protect the equipment and the frame from potential damage by sliding missiles. Potential damage to the slabs caused by the missile tail hit was also taken into consideration while specifying the parameters of these tests.

In tests IB1 and IB3 with the slab inclinations of 20°, the projectiles slid sideways with subsequent missile tail impacts, as observed in the test FPI1. In the tests IB2 and IB4 with the slab inclinations of 10°, in contrary, only a slight lateral change of position of the missiles on the slab surfaces was observed.

Table 1: Data of the IB series tests (IMPACT IV-NEREID)

	TF11	TF12	IB1	IB2	IB3	IB4
Slab Dimensions	2.1 m × 2.1 m × 0.15m					
Bending Reinforcement	Ø 6 c/c 50 mm both directions and faces (5.7 cm^2/m)					
Shear Reinforcement	Ø 6 c/c 100/200 mm closed stirrups (56.5 cm^2/m^2)					
Inclination Angle [°]	0	0	20	10	20	10
Impact Velocity [m/s]	108.3	130.2	111.8	112.9	128.4	130.4

NUMERICAL MODEL

Method and Assumptions

Three-dimensional finite element analyses of IB tests are performed with LS-DYNA and SOFiSTiK finite element software.

Element Types and Material Models

In the LS-DYNA simulations, the slabs are represented by eight-noded hexahedron constant stress solid elements for the concrete and two-noded beam elements for the reinforcement. The missile pipes and the supporting frames are modelled with shell elements. Supporting steel bars, placed between the slab and its supporting frame, are modelled using solid elements.

In the SOFiSTiK simulations, the target is modelled with shell elements, which include a nonlinear layered concrete model with approximate consideration of nonlinear shear deformations. The shell elements are subdivided into 12 concrete layers, and the crosswise reinforcement at both faces of the structural elements is considered. The supporting steel frame and the four steel pipes, which are anchored to the wall of the test hall, are modelled by beam elements. The finite element models of the test IB1 are represented in Figure 1.

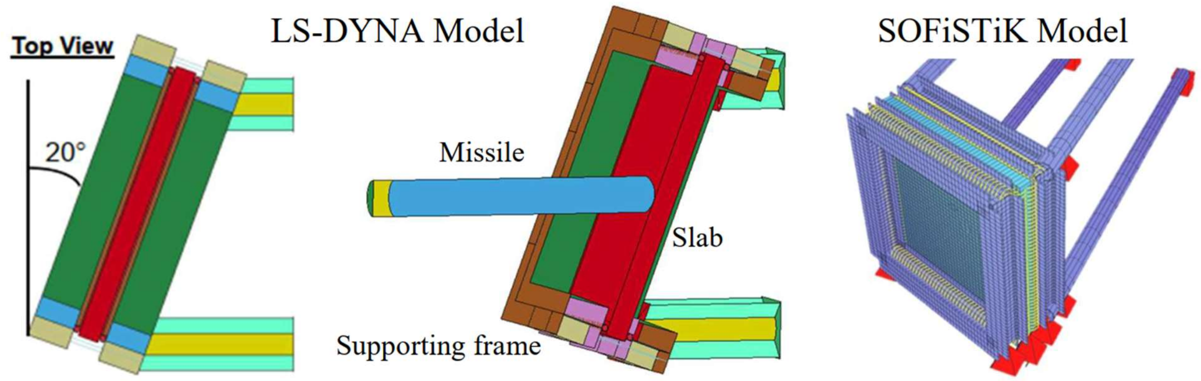

Figure 2. Finite element model of the test IB1 with LS-DYNA (left and center) and SOFiSTiK (right)

The Winfrith material model of LS-DYNA (material model 084-085) is used for the concrete. The concrete behaves elastic-perfectly plastic in compression not considering compression-softening.

Therefore, brittle compressive failure cannot be realistically simulated. The tension-softening allows for tensile failure to be modeled using this material model.

The constitutive model for the longitudinal bars and stirrups is bilinear with strain hardening. The concrete and reinforcement elements are assumed to have a perfect bond where the concrete solid elements are connected to the reinforcement beam elements at nodal points. The same nodes are defined for the reinforcement and the concrete where they are in contact with each other. The impacting missile and the supporting system are modelled using bilinear material models with strain hardening.

The nonlinear behavior of the reinforced concrete components in SOFiSTiK models is defined by:

- a nonlinear uniaxial stress-strain law of concrete considering compression-softening (including increase in strength due to biaxial compressive behaviour),
- consideration of tension softening of concrete after cracking as a function of the fracture energy,
- consideration of tension stiffening of reinforcement in the cracked state,
- approximate consideration of transverse shear deformations by an elastic/perfectly plastic shear stress/shear strain law after exceeding the specified ultimate shear strength and
- a tri-linear stress-strain law of reinforcing steel with strain hardening.

Loading and Support Conditions

For the coupled missile-slab analyses using LS-DYNA software, the initial position of the impacting missile is defined at the surface of the slab. The missile is then subjected to a predefined initial velocity. Contact surfaces are defined between the missile and the reinforced concrete slab, between the missile and the frame, as well as between the concrete slab and the supporting bars and frame. Due to symmetry, only halves of the test bodies are modelled.

The slab loading in the decoupled SOFiSTiK calculations, which is defined by force-time functions, is obtained from separate analyses of the impacting force plate missiles. The load is applied to a circular area in the slab center, the diameter of which takes into account the widening of the crushed projectile and the load distribution to the mid-surface of the slab. The lateral displacement of the load position due to the projectile slipping is not considered in this calculation. The slab support in the frame is represented by hinged couplings.

PREDICTED RESULTS AND COMPARISON

Initially the LS-DYNA software was used for modelling the inclined force plate test FPI1, varying the coefficient of friction. Based on the load time histories obtained from impact on a rigid wall, a simplified SOFiSTiK analyses was carried out for designing the tests, where the load-time histories were applied at a fixed position in the centre of the slab. After the FPI1 test was successfully performed, the comparison to numerical analysis resulted in a calibrated friction coefficient, which was smaller than expected. For this reason and due to the expected missile sliding and rotation, further calculations were carried out only in LS-DYNA software. The obtained results and the applicability of modelling criteria using both software programs are discussed and compared to the experimental data.

Force Plate Test FPI1

The numerical simulation of the force plate test FPI1 was performed with LS-DYNA, where the deformable projectile was represented using shell elements. A major parameter for modelling a possible missile sliding is the coefficient of friction assumed between the projectile and the plate. The numerical analysis with an impact velocity of 110 m/s and an inclination angle of 20° showed a substantial sliding of the projectile assuming a friction coefficient of 0.2. The sliding obtained was very small for a friction coefficient of 0.4. Despite sandblasting the plate surface, experimental results were similar to those of the simulations assuming a friction coefficient of 0.15 and 0.2 as shown in Figure 3.

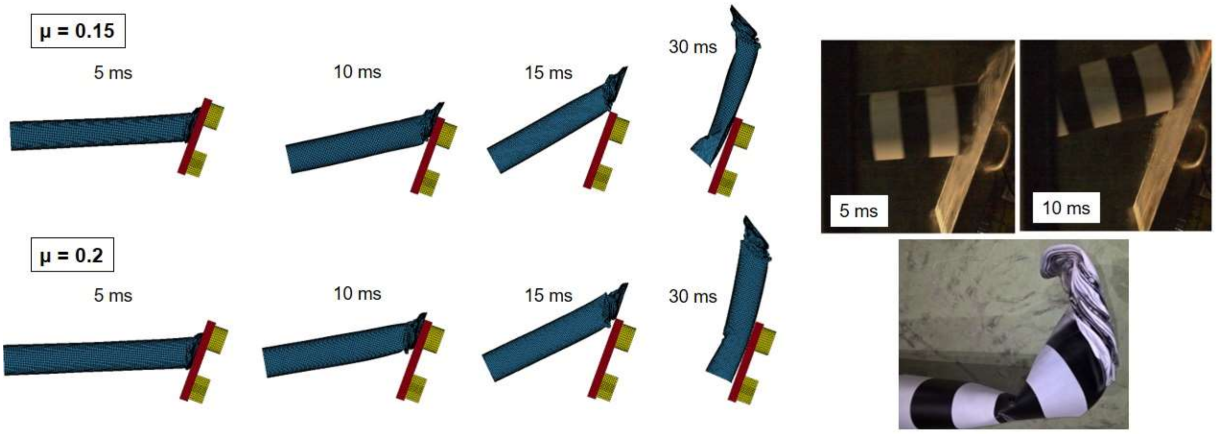

Figure 3. Missile behavior of the test FPI1 obtained from LS-DYNA (left) and test results (right)

Figure 4 shows the impact force time history calculated with the coefficient of friction of μ = 0.15 compared to the measured force time history. From the good agreement between calculation and measurement it can be concluded that the coefficient of friction between the projectile and the steel plate is closer to μ = 0.15 than to μ = 0.2.

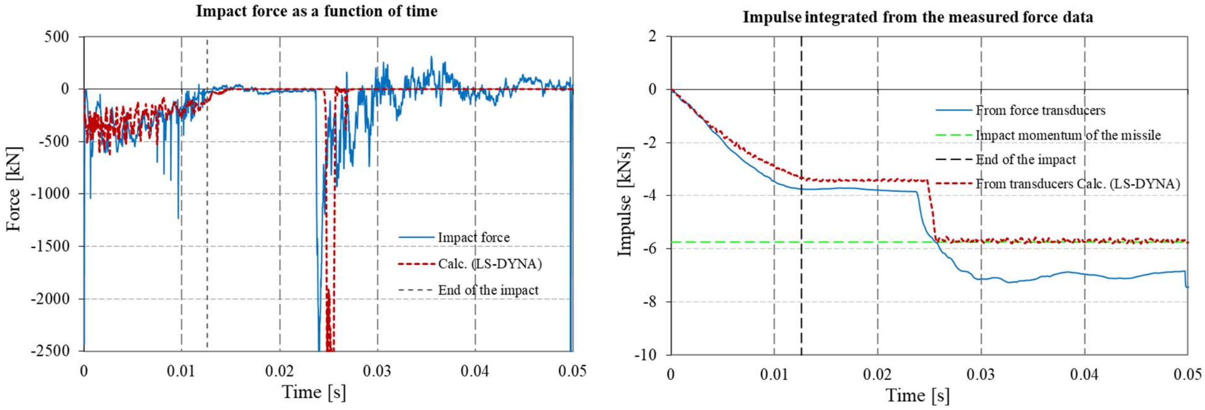

Figure 4: Impact load time histories of the test FPI1 and their impulses (friction coefficient μ = 0.15)

Missile Response, Slab Tests

The comparison of the missile response for test IB1 (20° slab inclination) with an impact velocity of V=110 m/s assuming a coefficient of friction of 0.2 between the missile and the slab is shown in Figure 5. The still frame images at different time points of the simulation are compared to the experimental captures. The missile slides and hits the side frame 20 ms after the beginning of the impact. It then continues to rotate and the projectile tail hits the slab for a second time at 30 ms similar to the experiment. A wooden plank was used to protect the side frame in this test. The missile was stuck at the side of the frame below the wood during the experiment.

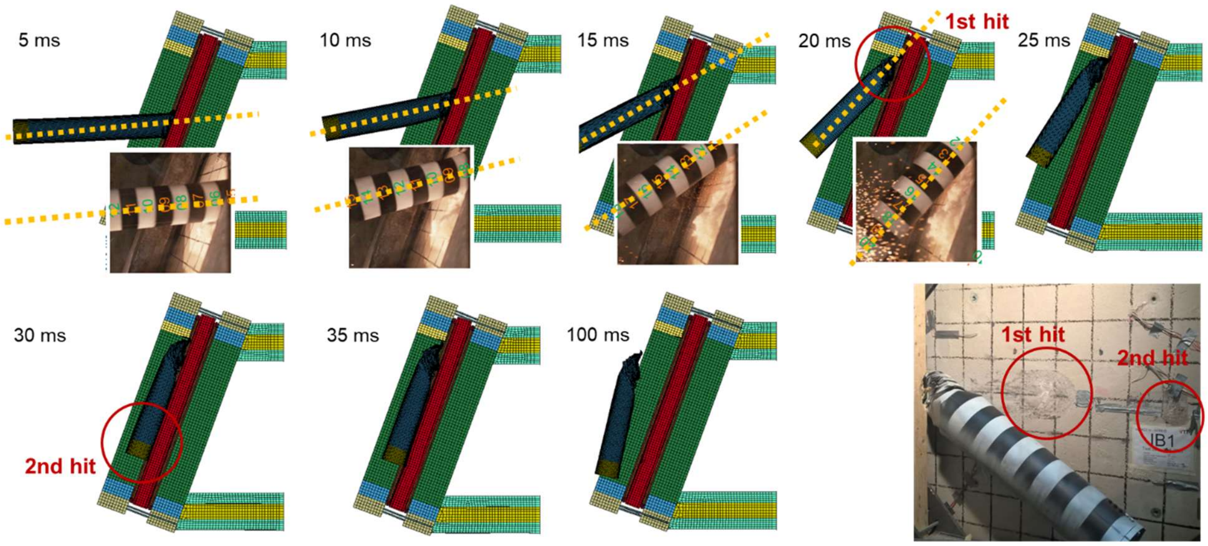

Figure 5: Calculated and experimental missile response for the test IB1 (20° inclination)

Deflection Time Histories

Figure 6 shows the influence of the different inclination angles on the measured and the calculated slab displacement for different sensors in the impact direction. Assuming a coefficient of friction of $\mu = 0.2$ for the impact angle of 20° and $\mu = 0.4$ for the impact angle of 10°, the LS-DYNA simulations show a good agreement with the measurements for the tests with V = 110 m/s (TF11, IB1, and IB2). The displacements due to the second impact of the missile tail in test IB1 are also well captured.

For the tests with V = 130 m/s (TF12, IB3, and IB4) the displacements are compared in Figure 6 (bottom). The LS-DYNA simulations show a good agreement to the measurements assuming $\mu = 0.2$ for the impact angle of 20° and $\mu = 0.4$ for the impact angle of 10°. The SOFiSTiK results applying impact load-time-histories predefined for $\mu = 0.4$ also provide a reasonably good match to the maximum measured displacements. However, a second impact due to missile rotation cannot be simulated using this decoupled method as seen in the comparison for the test IB3.

The maximum displacements decrease with the increase of the impact angle as expected. The displacements decrease up to 40% with an increase of the inclination angle from 0° to 20°.

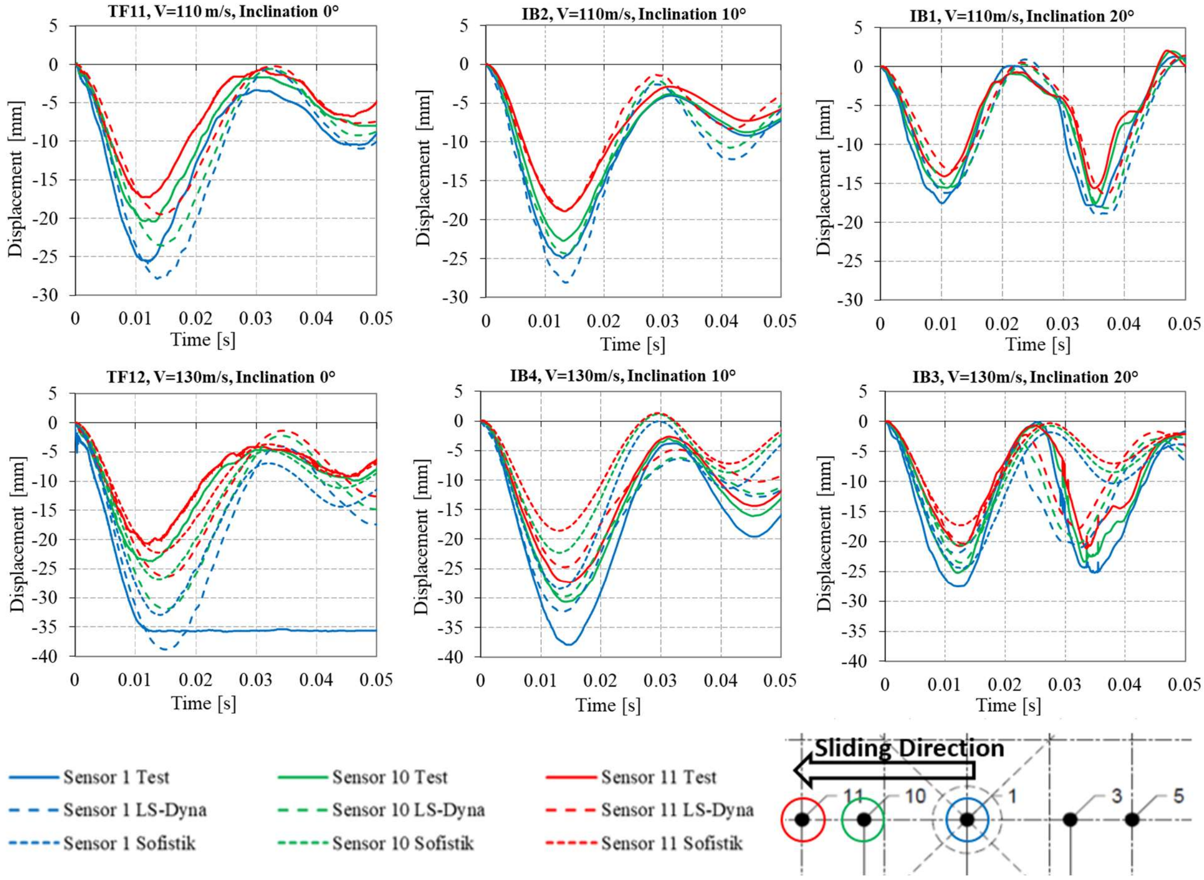

Figure 6: Comparison of the calculated and measured displacements for the tests TF11, IB2 and IB1 with V =110 m/s (top) and TF12, IB4 and IB3 with V = 130 m/s (bottom)

Support Reaction Forces

The total support reaction force-time histories in the impact direction obtained with LS-Dyna are compared with the test data in Figure 7. The support forces obtained from finite element analyses are the contact forces between the slab and the supporting bars in the loading direction, whereas the experimental values are measured at the four pipes behind the supporting frame (see Figure 1) and then summed up.

The comparison shows that the calculated support reaction forces and their vibration frequencies match the measurements well. However, the peak values from the numerical models are lower than those measured during the experiments. This is mainly due to the simplifications in defining the support boundary conditions in the numerical models.

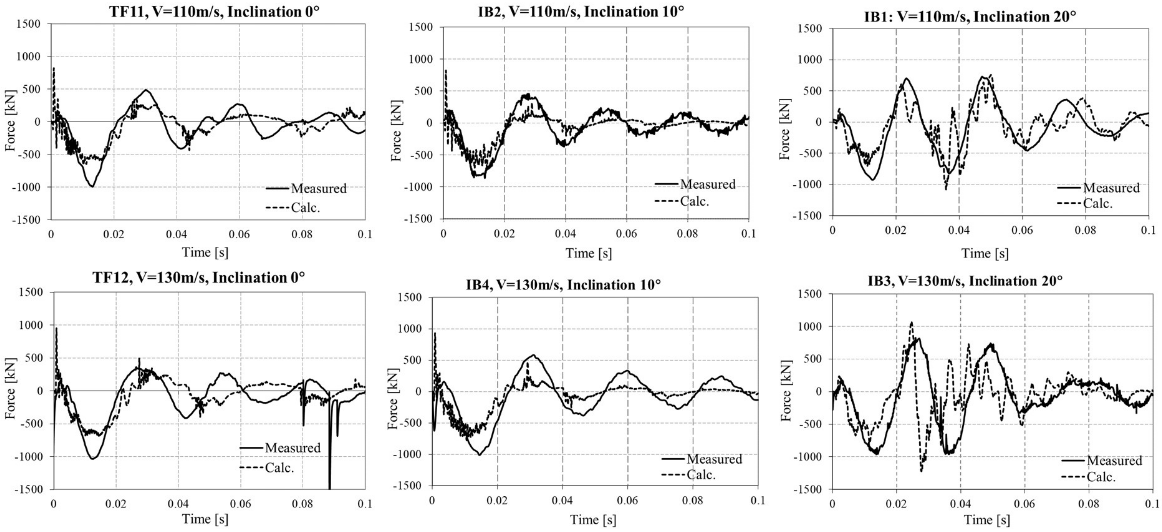

Figure 7: Comparison of the calculated and measured support reaction force-time histories

Reinforcement Strains

The LS-DYNA bending reinforcement strain-time histories are compared to the measured values for two strain gauges (one at the slab center and one at a diagonal location) in Figure 8. The bending strains at the slab center (gauge 6 for test TF12 and IB4) were underestimated. This may indicate localized stress concentrations at the locations of these sensors during the experiments, which can be confirmed through loosening and loss of this gauge in the test IB3. The calculated strain-time history of the test IB3 for the gauge 5 (also close to the slab center) matches the measured strain very well. The calculations correspond well to the measured values of the gauge 1, but the maximum values are underestimated for test IB4.

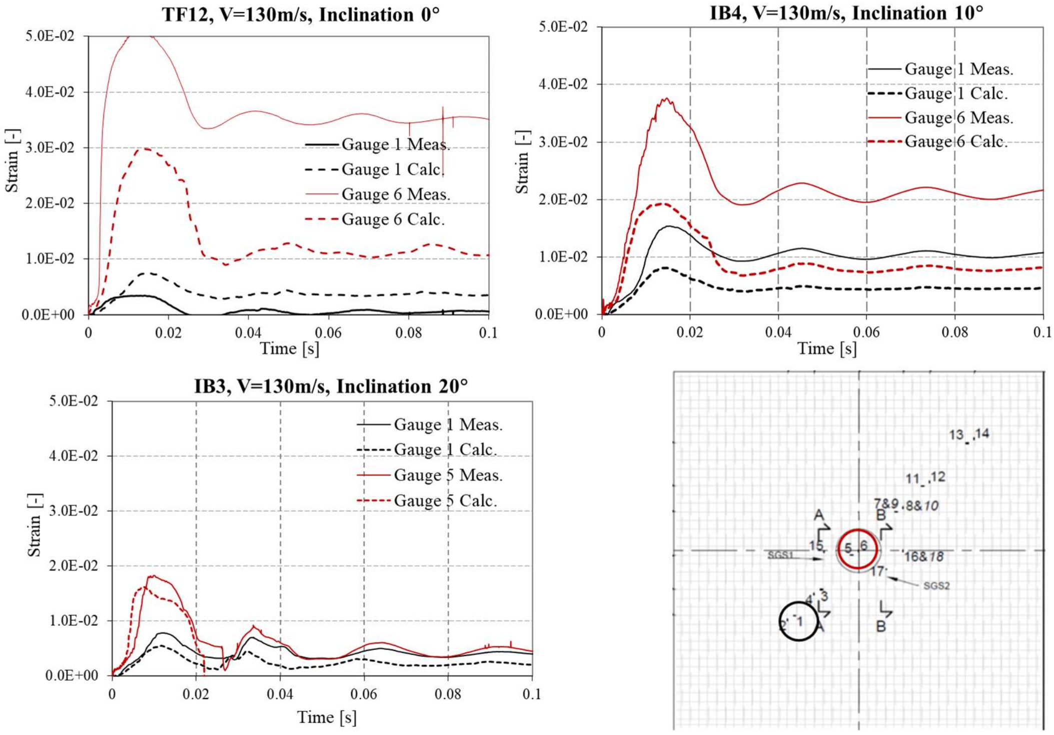

Figure 8: Bending reinforcement strains

Coefficient of Friction

The coefficient of friction (μ) between the missiles and the slabs was calibrated by comparing the simulations with different coefficients μ to the experimental response. After carrying out the force plate test FPI1 with 20° inclination it was concluded that despite sandblasting the surface, the coefficient of friction between the missile and the steel plate was about 0.15. Based on this outcome, the slab response of the IB tests was explored assuming coefficients of friction of 0.2 and 0.4. For the tests with 10° inclination the coefficient of friction of 0.4 provided a good match to the experimental response, whereas for the tests with 20° inclination the coefficient of friction of 0.2 was found to be more representative.

These coefficients, however, were input as static coefficient of friction in the numerical analysis. The possibility of defining a “single set” of parameters assuming different static and dynamic coefficients of friction, which can provide reasonable calculations for both inclination angles, is considered here.

The relationship between the static and dynamic coefficients of friction and the sliding velocity is defined in LS-DYNA using the following equation (according to the Keyword User’s Manual, Volume 1):

$$\mu c = FD + (FS - FD) \cdot e^{-DC \cdot vrel}$$

where *FS* , *FD* , *DC*, are the static and dynamic coefficients of friction, and a numerical decay coefficient, respectively. *vrel* represents the relative sliding velocity. The maximum measured sliding velocities were about 60 m/s for the tests with the 20° inclination and about 10 m/s for the tests with 10° inclination. Using these measured sliding velocities in combination with the calibrated coefficients of friction of 0.2 and 0.4, a curve can be fitted to represent the varying coefficient of friction as shown in Figure 9 (left). This curve can be used in LS-DYNA to define the friction between the contact surfaces. The measured displacement-time histories of the sensor 1 for the tests IB1 and IB2 are compared to the calculated ones using this friction curve and the ones calculated using static coefficients of friction in Figure 9 (right). The comparison shows that the friction curve provides a good match for both 10° and 20° inclination angles. However, it is not possible to give a solid/universal recommendation based on this comparison since this curve is fitted using only two points (for 10° and 20° inclinations) as seen in Figure 9 (left). Further tests with different inclination angles may be necessary in order to obtain a universal curve for defining the coefficient of friction for numerical analyses of inclined impacts on reinforced concrete slabs.

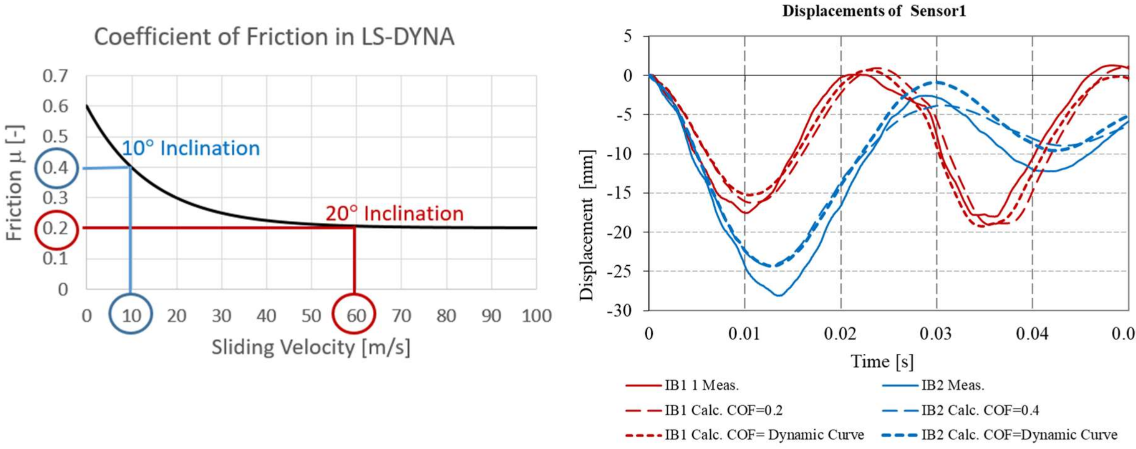

Figure 9: Fitted curve for dynamic coefficient of friction in LS-DYNA (left) and the calculated results using the curve (right)

CONCLUSION

Numerical analyses have been carried out using two different finite element software programs for the prediction of the inclined bending tests IB1, IB2, IB3, and IB4 of the IMPACT IV project. The aim is to explore the capability of the finite element methods to replicate the impact response of inclined reinforced concrete slabs. The analyses, which were calibrated with the TF11, and TF12 reference tests of the IMPACT II project, performed well in predicting the overall response of the slabs. The calculated displacement time histories correspond well to the measurements using both SOFiSTiK and LS-DYNA software. The maximum values of the displacements are slightly underestimated. The maximum displacements decrease with the increase of the impact angle as expected. The displacements decrease up to 40% with an increase of the inclination angle from 0° to 20°.

The bending strains are generally well predicted, but the maximum values at the slab centre are partially underestimated due to the localized concentration of the stresses. The calculated support reaction forces match well the experimental data.

For the implicit analyses, using SOFiSTiK, the loading (force-time history) has to be predefined. The explicit analyses using LS-DYNA, on the other hand, have the advantage of simulating the interaction between the missiles and the slabs, in which the sliding and rotation of the missiles and a possible tail hit can be simulated if a correct coefficient of friction is assumed between the projectile and the target. A friction curve was calibrated and fitted in this study, which provided a reasonable assumption for the two inclination angles of 10° and 20° tested here. However, since the curve is adjusted using only two different inclination angles and is not supported with further experimental studies, it should not be taken as a recommendation but as a general guide on how to define the friction for such problems.

REFERENCES

Fedoroff, A., (2021). IMPACT IV – NEREID IB test series report, *VTT Research Report*, VTT-R-00359-21.

Livermore Software Technology Corporation (LSTC), an Ansys Company: LS-DYNA Software, Version LS-DYNA R11/R12, Keyword and Theory Manuals.

Tarallo, F., and Rambach, J., M. (2013). Some Lessons Learned from Tests of VTT IMPACT Program, Phases I and II, *Transactions, SMiRT 22*, San Francisco, USA.

Vepsä, A., Calonius, K., Hostikka, S. and Tuomala, M. (2013). Medium Scale Testing and Simulation of Aircraft Crash, *IABSE Symposium*, Safety, Failures and Robustness of Large Structures, Helsinki, Finland, pp. 234-241, DOI: 10.2749/222137813807054656.