Numerical investigation of Reinforced Concrete behavior under external or internal aggressions through modelling in fast dynamics

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Abstract: The prediction of Reinforced Concrete (RC) behavior in nuclear structures undergoing loads within the fast dynamics domain remains a challenge for the safety assessment. Such loads include impact and explosion accidental configurations and may require the use of advanced nonlinear numerical models especially when loads are beyond design. Verification and validation of these models based on reference experimental data is what ensures a proper identification of the validity domains and a relevant extrapolation to the structural scale. To reach such goal, ASNR is a partner of the IMPACT project, which is led by the Technical Research Center VTT (Finland) aiming at understanding the dynamic behavior of the RC structures. Those tests consist of launching a projectile (soft or hard) with given speed onto RC walls and steel plates and measuring the resulting forces and deformations within the projectile and the structural element being tested. Based on the obtained experimental results, ASNR achieved a series of numerical simulations exploring several behavior laws to allow a physical interpretation of the tests and an accurate model calibration (fitting of nonlinear law parameters). As an extension of such modelling work, the same behavior laws are then used to simulate the effect of an explosion (steam explosion) on the behavior of internal structures including the shield walls of a nuclear reactor. The simulations provide qualitative and quantitative results including damage mapping; displacement and plastic strain of reinforcement bars. For such full-scale applications, there is no possibility to access this information through the real tests; so, the numerical model validity and sensitivity analyses are mandatory prerequisites to trust the physical representativeness of the obtained results.

1 INTRODUCTION

For nuclear safety assessment, accounting for internal and external aggressions is one of the challenges to consider for deterministic studies and probabilistic ones in the framework of Probabilistic Safety Assessment (PSA). The source of these aggressions on civil engineering structures can be external such as the projectile impact including civil aircraft impact or internal such as explosion following severe accident scenario. Quantifying the effect of these aggressions requires a comprehensive understanding of the fast dynamic response of the RC and the associated structural behavior. Several key questions still need answers such as the effect of impact or explosion on the local behavior (deformations, cracking pattern) and global one (total load and stability issues) in addition to the effect on induced vibrations on the equipment and structural elements away from the impact zone.

To advance on this issue, ASNR joined the IMPACT project since 2006 covering several phases from 1 to 4 [1, 2, 3]. In each phase, the designed RC walls are built with different combinations of reinforcement ratios, geometrical scale factor and thickness/stiffness of the projectiles. During each experiment, the cracking pattern, reaction force and out-of-plan displacement are recorded. In the first part of this paper, we present the improvement of our simulation by comparison to the available measured results, with the consideration of a compromise between model simplicity and the results accuracy. The developed simulations are based on the LS-DYNA finite element software [4] with the explicit solver. The obtained results reveal a good prediction of the global behavior of the RC wall (see the SMiRT28 paper for more details [5]). Once our model (behavior law of RC concrete under impact) considered valid, it is applied to other loading configurations beyond the framework of the IMPACT project. This concerns particularly the case of internal aggressions due to steam explosion inside the containment building. In this case, the core meltdown leads to a risk of fuel coolant interaction (FCI) and results as an important steam explosion at ex-vessel. This type of explosion in extreme conditions might reach about 40 MPa in less than 10 milliseconds (ms) based on the studies of SERENA project [6]. Those calculations are (by definition) beyond design and aim at assessing the consequences of such accidental loadings on the structural and functional performance of the nuclear containment buildings. These concerns (a) mechanical stability of the local shield wall and internal structures (b) the leak tightness of the containment building (ability to maintain radioactive substances inside the building). So, the paper presents in its second part the simulation of a full-scale internal structure of the containment building. Pressure loadings are obtained from previous computational fluid dynamics (CFD) using MC3D software [7]. The results of the simulations allow the understanding of the response of the internal structure in these situations (damage map evolution as a function of the loading) and also quantifying its performance based on the simulated strains and stresses in concrete and steel rebars and based on the lateral drift of the internal structures to assess the risk of interaction with the inner containment wall. Though not presented in this paper, one can mention that such modelling is done for several configurations to allow for uncertainties propagation coupled to metamodeling techniques to limit the computational cost which can be useful for PSA.

As a nuclear regulatory body, the ultimate aim of these calculations is to challenge modelling hypotheses usually considered by operators and provide useful insight for the evaluation of the technical validity of margin results obtained by utilities.

2 THE IMPACT PROJECT – from experiment to modelling

2.1 Overview of the experimental campaign

Several specimens are constructed and tested within the IMPACT project using the same experimental installation. In this paper, we present one case which corresponds to test X2 of the IMPACT III [2]. In Figure 1, the RC wall is 2m x 2m x 0.25m, and it is installed between the steel frames (supporting structure) with tightened screws. Supposedly fixed and rigid support is considered through the horizontal steel beams that are connected from the steel frame to the back rock structure.

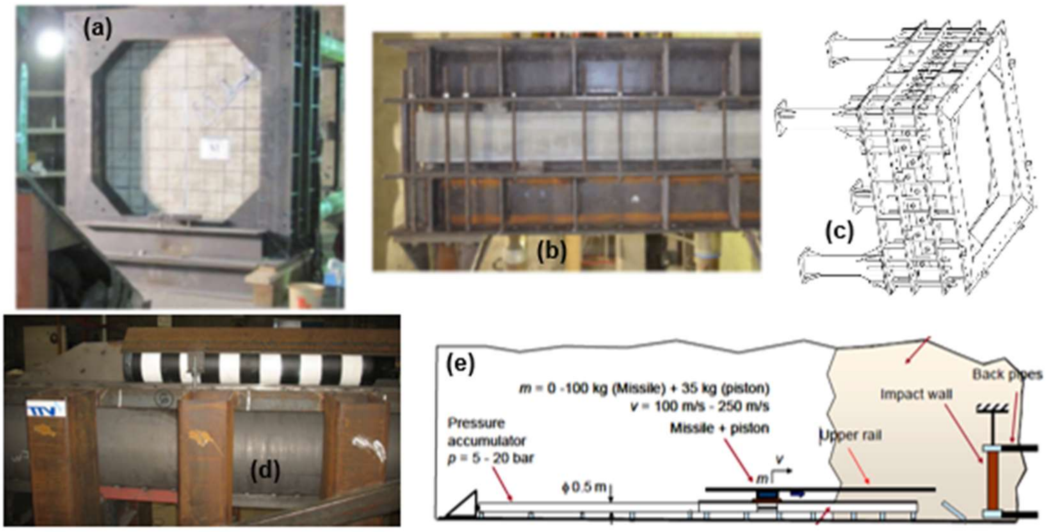


Figure 1:the experiment installation, (a) RC wall; (b) tightened screws; (c) supporting structure; (d & e) projectile setup

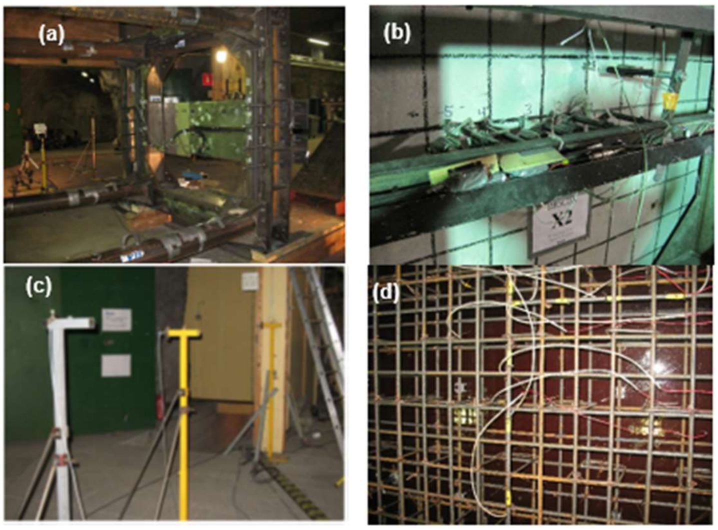


Figure 2: the measured sensors, (a) reaction force, (b) displacement, (c) velocity, (d) strain gauge

The projectile is projected through a steel tube by an accumulator of compressed air to achieve a given velocity at impact. For test X2 of interest here, the missile is projected perpendicularly to the RC wall at a speed of 164.5 m/s. During the test, the reaction forces (force obtained at impact on a supposedly rigid body), out-of-plan displacements, strain gauge, missile velocity are recorded (see in Figure 2). Nevertheless, due to the complexity and high vibration effect, certain sensors are lost during the test (this was the case of displacement and strain gauge in test X2 for instance).

2.2 Overview of the numerical model

As illustrated in Figure 3, the numerical model for the mock-up consists of the supporting structures, the concrete wall, the reinforcement bars and the missile. The supporting structure is modeled using shell elements with a linear elastic behavior. The concrete is modeled by solid elements with the nonlinear damage model (MAT_159_CSCM n LS-DYNA). This model is selected after sensitivity study covering all damage laws available in LS-DYNA (the model performs well and provides an acceptable computational time). The missile and rebar are modeled by shell and 1D elements, respectively. An elastoplasticity model is applied for both components. The necessary input parameters for the constitutive models are obtained from the measurement on the sample scale. The boundary conditions are applied as these of experimental installation, and a constrained displacement is made between front and rear steel frames to avoid of modeling the screws (this is a simplifying hypothesis since the pressure of screwing is unknown). The contact is modelled for the missile and RC wall (contact between elements of the same body and contact with elements from other bodies).

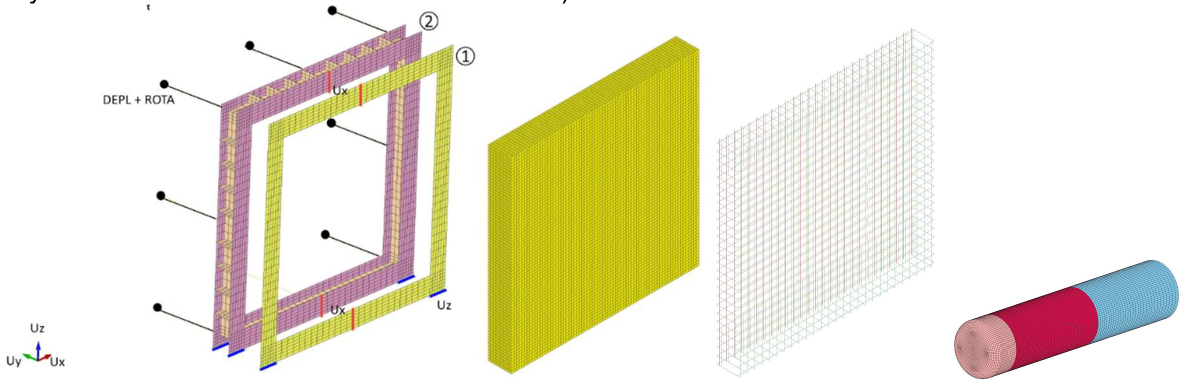


Figure 3: numerical mock-up for test X2 *[5]*

The comparison of the results between the simulation and the experiment are summarized in Table 1.

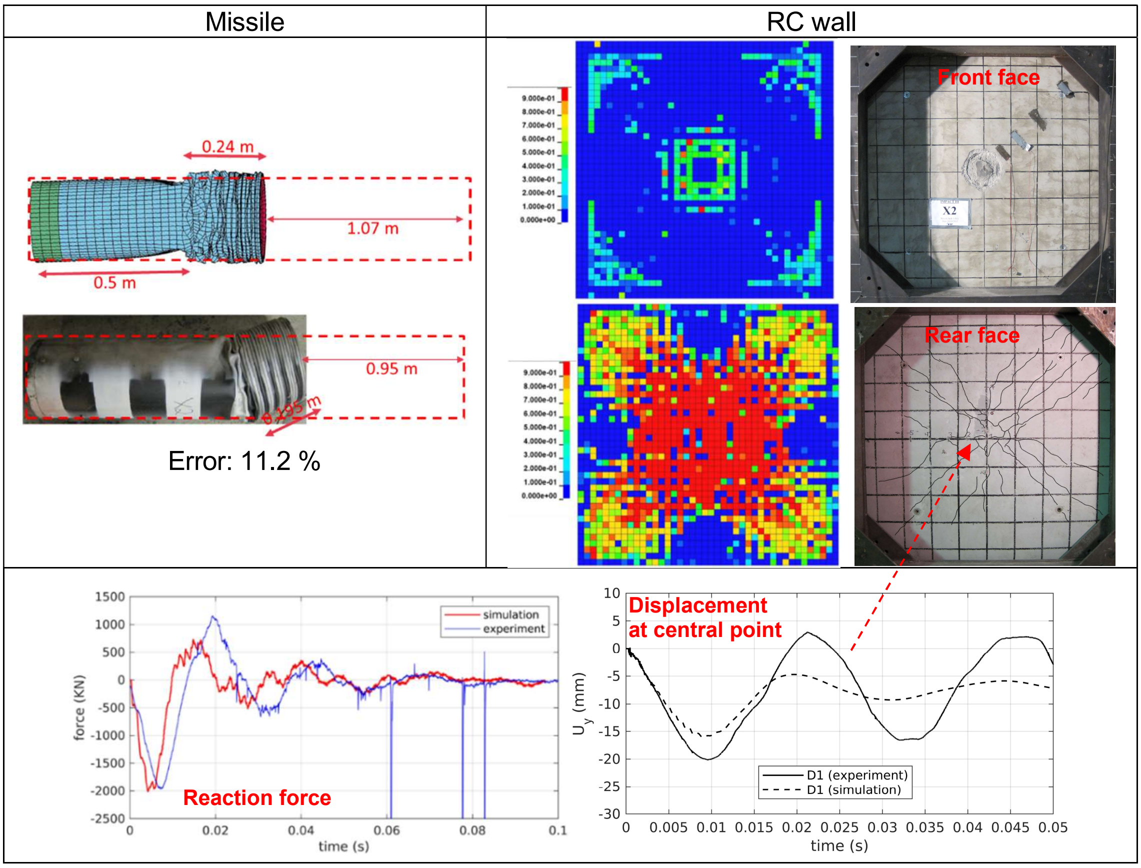


Table 1: summary of the comparison between the simulation and experiment *[5]*

The simulation predicts a similar deformed configuration of the missile with a relative error of 11 % for the deformed length. Moreover, the damage distribution in wall on the front and rear faces are coherent with the one observed after the experiment. The estimation of the total reaction force and out-of-plan displacements (central point and rear face) give a good agreement in comparison with the measured results. Overall, when the boundary conditions are well represented and material properties well defined, the developed numerical model seems to provide accurate global response of the RC wall under impact.

3 CASE STUDY OF INTERNAL EXPLOSION

3.1 Overview of the accidental configuration

The explosion is considered as an accidental situation and might result from different circumstances such as the leakage of hydrogen gas in certain local areas in the auxiliary buildings for instance, fuel coolant interaction (FCI) at ex-vessel in the reactor building, etc. Those explosions would generate high pressure in just a few milliseconds (ms) which reach the civil structure or equipment. As described, the paper selects a case study of the FCI for performing fast dynamic simulation, see in Figure 4. The extreme pressure loading is limited to the local shield wall structure where the vessel is installed. The explosion in this specific zone might induce a shock from the lateral displacement of internal structure to the containment building (CB), in addition to the risk of instability of the internal structure.

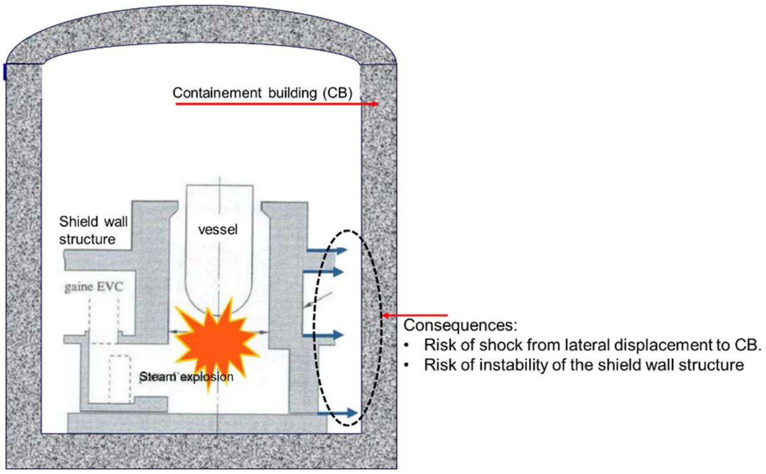


Figure 4: case study of steam explosion in shield wall structure under FCI

3.2 Overview of the numerical simulation

The simulation is performed with LS-DYNA and explicit solver. The full-scale internal structure is modeled by the solid elements for the concrete and 1D elements for the rebar, see in Figure 5. A fixed boundary condition is considered for the bottom surface of the raft foundation, whereas a perfect bond is assumed for interface of rebar-concrete. Inspired from the simulation developed in IMPACT project, the same material constitutive models are applied to concrete and reinforcement (different material properties though). In Table 2, a summary of a complete chain of the simulations is presented. The pressure distribution is obtained from the CFD simulated through MC3D [7] to include the pre-mixing phase and explosion phase. In fast dynamic simulation, we project those pressure profiles to the internal surface of the shield wall. The vessel is not modeled, but an equivalent dead weight is considered.

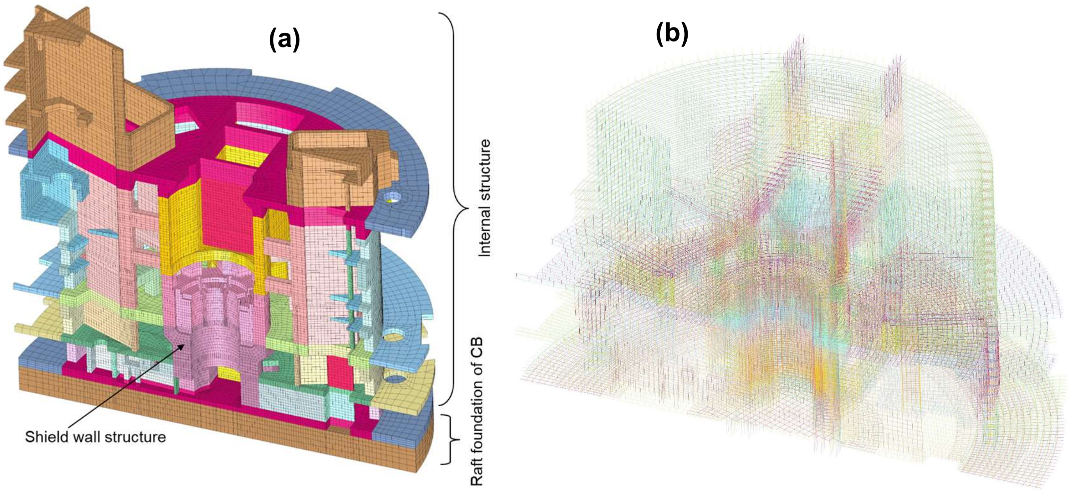


Figure 5: numerical mock-up of the internal structure viewed in cross section, (a) concrete, (b) rebar

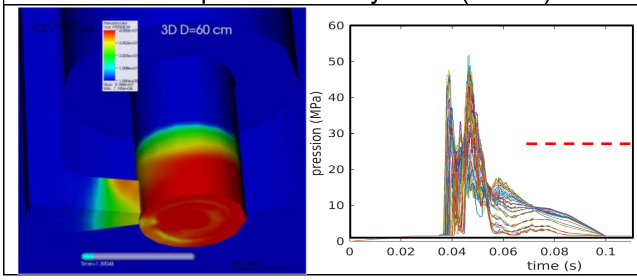
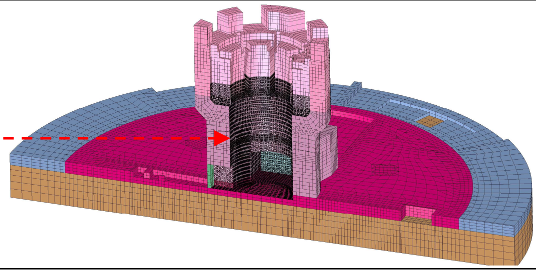
1. Computation fluid dynamic (MC3D)	2. Fast dynamic simulation (LS-DYNA)
	

Table 2: overview of a complete chain of simulations

3.3 Results and discussion

In Table *3*, the lateral displacement and damage distributions are illustrated. The important damage is localized at the shield wall and the maximum displacement of the floors close to the containment building (CB) is found at about 5 cm (10 cm is the minimum gap between the CB and internal structure). Besides that, the damage distribution is observed at the shield wall and extends to the adjunctive elements including slabs and walls. Such damage level in the shield wall impacts the stability of the internal structure. An analytical estimation of cross section strength [8] is achieved then for investigating different failure modes (shear and bending) obtained from the fast dynamic simulation. As we observe plastification in steel reinforcement bars, a horizontal through-cut in the shield wall is done to integrate the total force applied on the cross RC section. Here, we find that the most critical failure mode is due to shear loads (sliding and bending modes are secondary) and shear rebars are solicited once the concrete elements are strongly damaged.

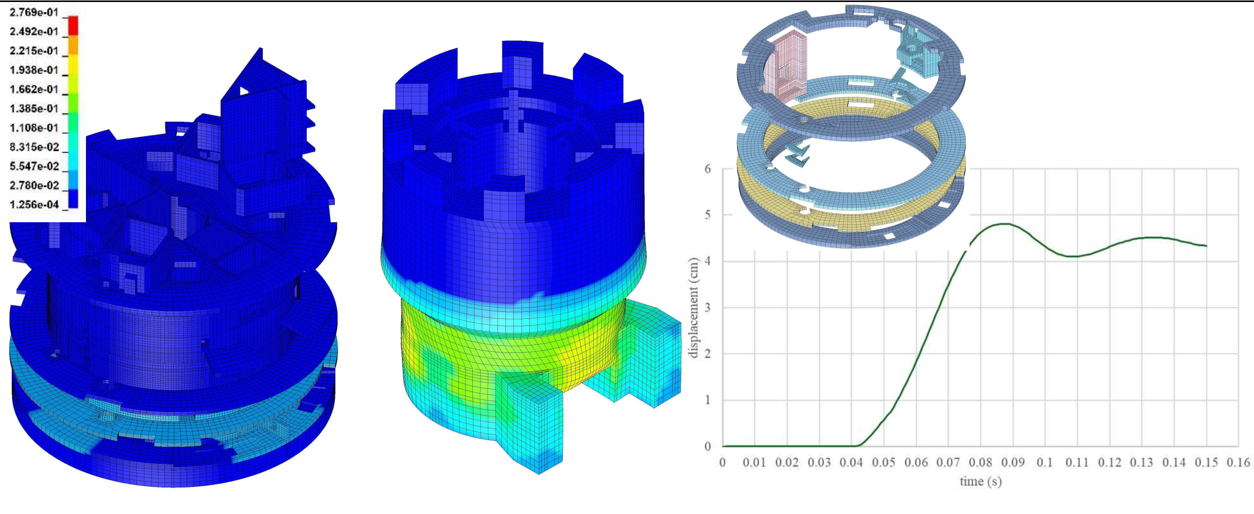
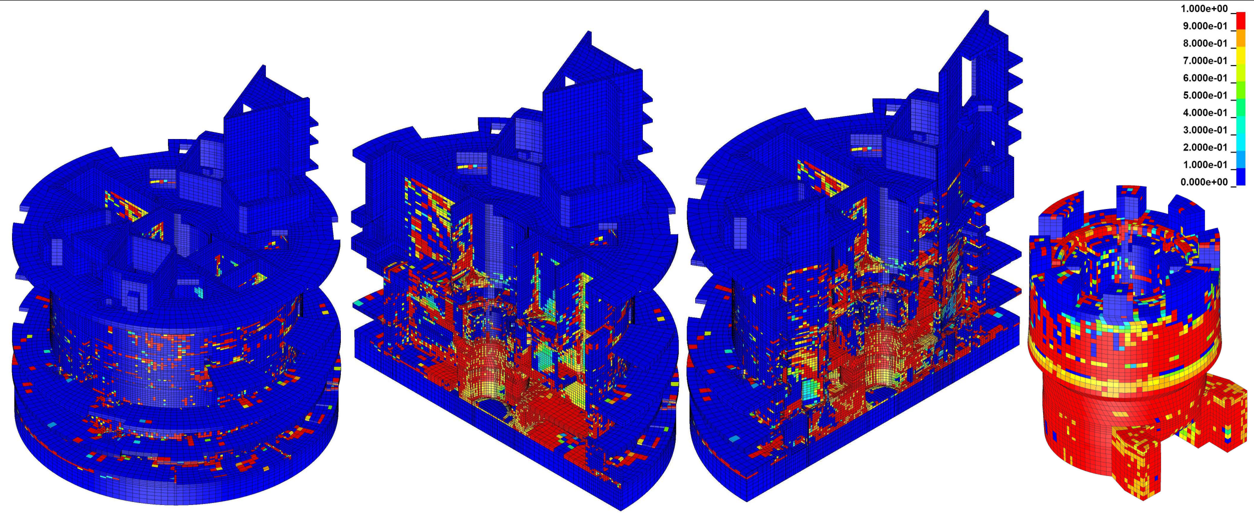
Lateral displacement	
Damage distribution	

Table 3: summary of the results of the fast dynamic simulation

4 CONCLUSIONS

In this paper, we present a study methodology retained by ASNR to achieve fast dynamics simulation. The first step consists of exploring the sensitivity analysis of available behavior laws of RC elements under impact and identification of associated validity domains. An example of this work is demonstrated here through the IMPACT experimental project led by VTT with several partners including ASNR. We show here a particular example of a mock-up wall under impact of a semi-rigid projectile. Numerical results compared to experimental ones include the deformed configuration of the missile, damage distribution in concrete, total reaction force and out-of-plan displacements. They are close and coherent with each other. In addition to sensitivity analysis of behavior laws, ongoing work covers the sensitivity to the perfect bond model (between rebars and concrete) and strain rate effect to the material properties. In its second part, the paper covers a case study of FCI, where the shield wall of internal structure is subjected to high and fast pressure loading (explosion). The choice of materials constitutive models is inspired by the IMPACT work (feedback on the validity domain of the used behavior law). A full-scale structure is modeled and aims at having a full characterization of stress, strain and damage distributions from the local explosion zone to the rest of the structure. The explosion pressures are applied as a 3D map projected on the inner surfaces of the shield wall. Those pressure time-histories are the result of a priori CFD computation using MC3D software. Post-processing of the numerical results is achieved to allow for the quantification of structural stability of shield wall and other RC elements (walls and floors) under shear and bending forces or sliding forces at casting joints. In addition, post-processing include the lateral drifts or displacements of floors and the risk of inter-shock with adjacent inner containment wall. This case study serves as an illustration of our complete chain of calculations for the FCI situation. In addition, though not mentioned in the present paper, we underline here the sensitivity of the mechanical response of the structure to the pressure profile and the need to include such variability since the pre-mixing phase prior to explosion assessment.

Both case studies illustrate a global study methodology adopted by ASNR to deal with the issue of fast dynamics: first identification of the model validity domain before the extension of the model applicability to full structural scales including uncertainties and sensitivity analysis. As a nuclear regulatory body, the aim of these calculations is to challenge modelling hypotheses usually considered by operators and provide useful insight for the evaluation of the technical validity of margin results they obtain.

ACKNOWLEDGMENT

This work is the result of a close and fruitful collaboration between ASNR and other members of the IMPACT project led by VTT. The consortium is thanked for their contribution to make the experimental platform available along with experimental data. Furthermore, the complete chain of computation of FCI is a collaboration between two units (LEPC for CFD computation, LMAPS for fast dynamic computation) within ASNR. The authors express their sincere thanks to the team members of LEPC for their contribution in providing pressure profiles. As for the PSA calculations that are not detailed here for the sake of conciseness, authors would like to thank colleagues from the SCEPS department (within ASNR) on the consideration of uncertainties and their propagation through the model.

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