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Some Experiences from HDR V31.1 and Applied LOCA Analyses on BWR and PWR

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1 ABSTRACT

There has been several papers and presentations made about HDR V31.1 simulations the last decade. We performed this simulation the first time in 2001, using ADINA-FSI. ADINA-FSI is the package that includes ADINA(FE), ADINA-CFD and the coupling code. Due to acceptable agreement with experimental data it opened up possibilities to perform applied LOCA analyses using commercial software.

In this paper we present three methods to perform simulation of the HDR V31.1 test. The original ADINA-FSI method is companied with the linear acousto-elastic method and a sequential method, that is a combination of the two. From the calculated results none of the methods seems superior to the others, but the computational cost varies greatly.

We also present experiences from some of the applied projects that we have performed. The difference between the HDR V31.1 simulation and applied projects is that the latter involves much more sophisticated structural models. In the HDR V31.1 case the structural response was linear. In the applied projects non-linearities must be included in the structural model. Since the solver time has been increased for the structure, it has forced us to simplify where possible to keep the computational cost at an acceptable level.

2 INTRODUCTION

The simulation of LOCA (loss of coolant accident) for reactor pressure vessels (RPV) has had a renaissance the last decade. The reason is that commercial software makes it possible with affordable computer resources to perform coupled analyses, unlike the original HDR simulations in the 1980s.

As validation case, simulation of the HDR V31.1 test is used by us and other organisations. See Wolf (1982), Andersson et al (2002), Andersson et al (2003), Sussman and Sundqvist (2003), Timperi et al (2008), and Brandt et al (2008).

In this paper we present three different methods to perform numerical simulation of this test. The first method is the same as we presented in Andersson et al (2003), although it is set up and solved again.

In 2005 we calculated vibration problems, using a coupled model with the linear potential based fluid in ADINA. Since this model is completely linear, to be able to perform linear structural dynamics, we call these models acousto-elastic. More insight of acoustic problems (by us and others) led to the conclusion that this acousto-elastic model could be used also in LOCA analyses. The pressure boundary condition usually used must then be exchanged to mass flux, which caused new problems and insight to us.

In 2006 an acousto-elastic model was set up and validated against the HDR V31.1 test. The results were again acceptable, but now the solver time has reduced to less than 1/100 of the first ADINA-FSI simulation. This is the second method we present below.

In 2008 we tested to perform a sequential simulation of the HDR V31.1 test. The idea is that a acousto-elastic FE model incorporates the correct 2-way FSI coupling between the motions of the structure and pressure waves in the fluid. The blowdown depressurisation waves are computed beforehand.

We also present some experiences from some of the applied projects that we performed for the Swedish nuclear industry during the 2000s.

3 THREE DIFFERENT METHODS TO SIMULATE HDR V31.1

The results in this paper consists of three separate methods to simulate the V31.1 test.

1.The coupled CFD-FE approach using iterative ADINA-FSI coupling, same method as in Andersson et al (2002).

2. The coupled acousto-elastic approach using fluid elements in the FE code, similar to Timperi et al (2008).

3. A combination of the above. A CFD simulation of the blowdown (without FSI) is mapped on a coupled acousto-elastic linear FE model. Hence, the fluid domain is represented twice. The purpose is to quantify the FSI effects. A similar approach is used by others where the blowdown is simulated in a thermo-hydraulic code and mapped to the acousto-elastic FE model.

Another method, using the subsonic potential based fluid in ADINA, was presented in Sussman and Sundqvist (2003) and is not further discussed in this chapter. We have validated it against HDR V31.1 as well and the results are very similar to the three methods herein. This method has been used thoroughly in our applied projects, see below.

3.1 The iterative 2-way ADINA-FSI numerical model

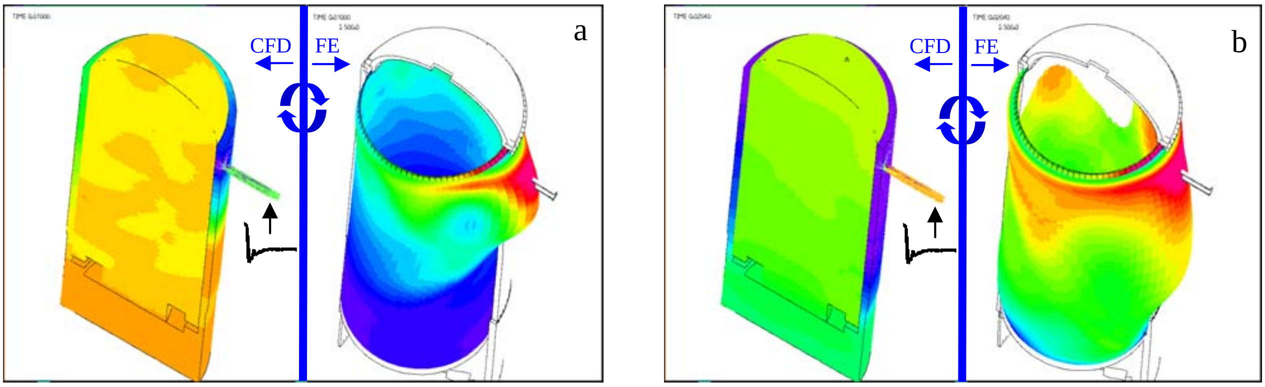

Figure 1. Pressure in fluid and von Mises stress on the deformed structure, after 10 ms (a) and 20 ms (b).

The CFD model consists of 75 000 elements which results in 80 000 DOFs. The fluid model used is inviscid, slightly compressible (constant speed of sound), has no turbulence model, and has slip condition at walls. The material properties are $\kappa = 0.82$ GPa and $\rho = 730$ kg/m^3. The initial pressure is 0 bar, and the measured pressure is used directly as boundary condition at the break location.

The FE models consists of 23 000 1st order shell and solid elements, 104 000 DOFs. The linear elastic material model is used with properties E = 175 GPa, $\nu = 0.3$ and $\rho = 7800$ kg/m^3. A small amount of Rayleigh damping is used.

The fluid solver governs the time step schedule, and here the Euler method with parameter $\alpha = 0.52$ is used. (trapezoidal rule with a small amount of numerical damping).

The iterative FSI coupling method is used, with no relaxation factors, and the default value of 0.01 for the tolerance criteria for both velocity and force. There is a possibility to use direct coupling of the fluid and structure matrices too, not further discussed herein.

For the first 15 ms a time step of 0.1 ms is used, the rest of the simulation time 0.2 ms is used.

The solution required less than 1 GB memory and took 18 000 s on 6 CPUs.

3.2 The acousto-elastic ADINA numerical model

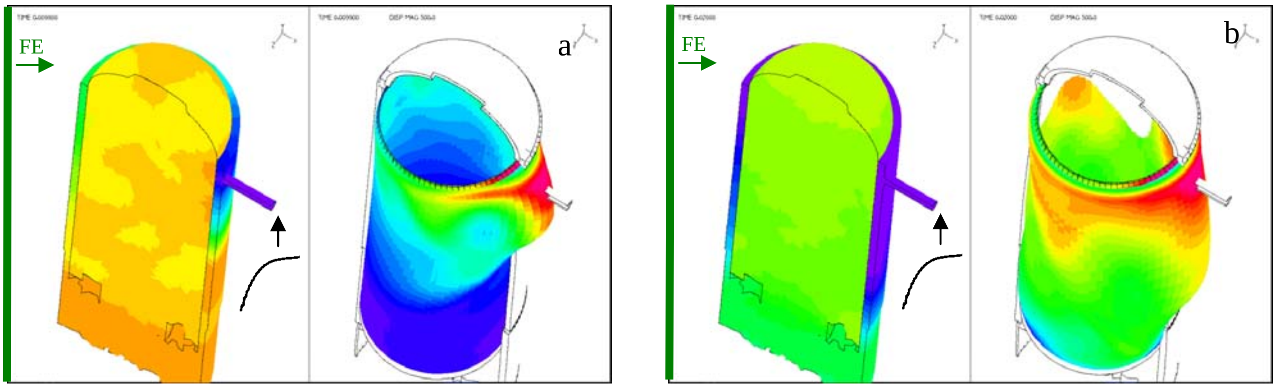

Figure 2. Pressure in fluid and von Mises stress on the deformed structure, after 10 ms (a) and 20 ms (b).

The structural part is identical to the FE model above. The fluid is modelled with 260 000 elements in the FE code ADINA. The total number of DOFs is 260 000. The fluid model is the linear potential based fluid with material properties $\kappa = 0.82$ GPa and $\rho = 730$ kg/m^3.

The load is applied as the prescribed mass flux at the break location. The measured mass flux cannot be used directly, since it contains too few samplings. Instead, the subsonic version of the fluid model was used. On that model the pressure was applied, and then the computed mass flux could be obtained. The staircase appearance of the mass flux is due to the reflections back and fourth in the break nozzle, which is not captured in the measured data.

The Newmark time stepping algorithm is used with default values for the α and δ parameters (no numerical damping). The Rayleigh damping does only apply on structural elements, so the fluid is undamped.

The solution required 1.3 GB memory and took 800 s on a single CPU.

3.3 The sequential 1+2 way FSI model

This model is composed of the fluid and structure parts described above.

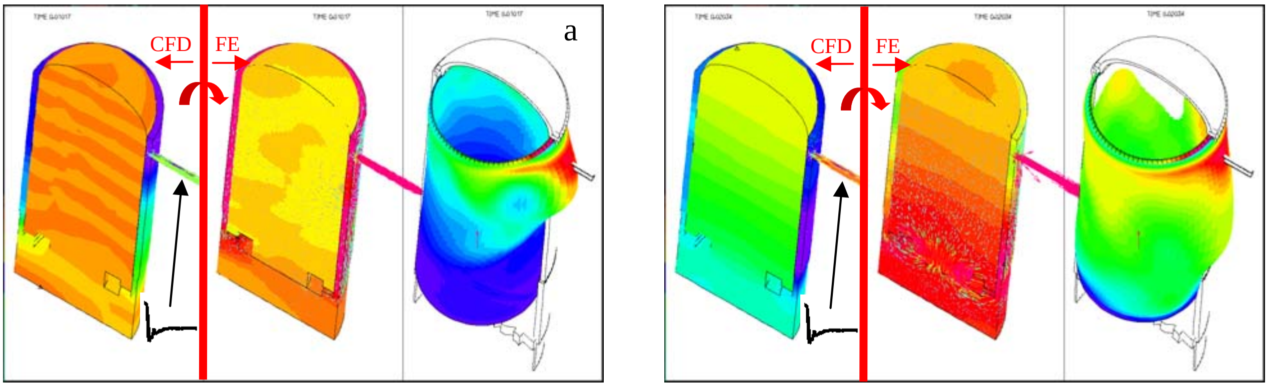

Figure 3. Pressure in CFD fluid, pressure in acoustic fluid, and von Mises stress on the deformed structure, after 10 ms (a) and 20 ms (b).

The CFD model is run first by itself, but the FE model must be defined so the appropriate fluid-structure boundaries can be identified. During the ADINA-CFD run the solver then creates a file incorporating the pressures that should be transferred to the FE model.

The FE model is the acousto-elastic model above. At the break location there is no load, instead the fluid potential is fixed which is a constant pressure condition. The FE model is thereafter run by itself, with the load file from ADINA-CFD. Hence, these pressures are applied at the fluid-structure interfaces, where also the interface elements between the acoustic fluid and structure are automatically created.

The same time stepping algorithms and time steps as above is used, and all other parameters like numerical and modelled damping were the same. The solution required 0.4 and 1.3 GB memory and took 8600 and 1600 s on 6 CPUs, for the CFD and FE part respectively.

4 RESULTS

In the previous figures the pressure, deformation and stress is shown for the three models. From these it is obvious that the results seems very similar. Here below, selected results, at some points where measurements were done in the HDR V31.1 test, are shown for comparison.

The measured data (black) is shown together with the three methods presented above. The 2-way iterative ADINA-FSI solution (blue), the sequential 1+2 way FSI (red) , and the linear acousto-elastic (green) results.

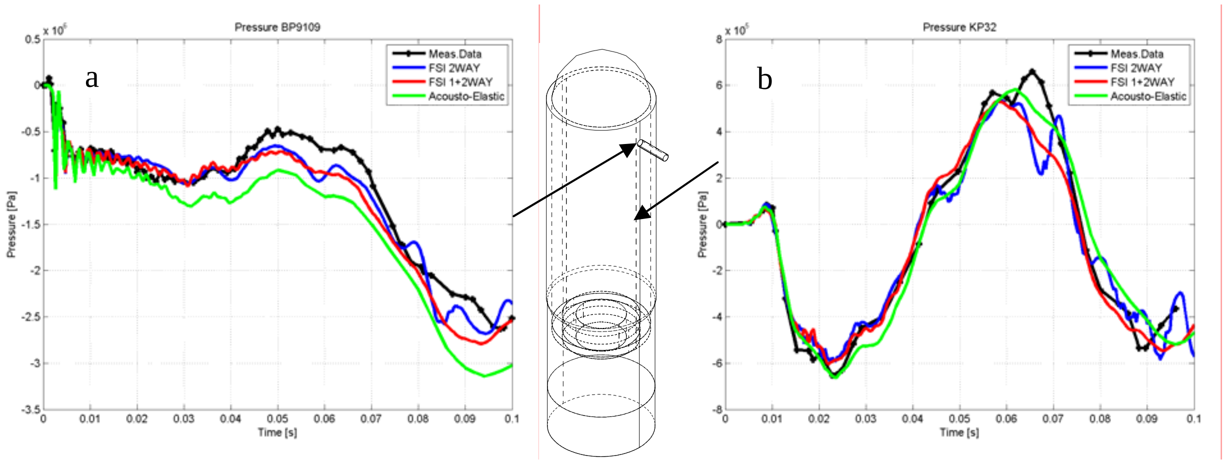

Figure 4. Pressure on downcomer wall (a) and pressure difference across downcomer wall (b).

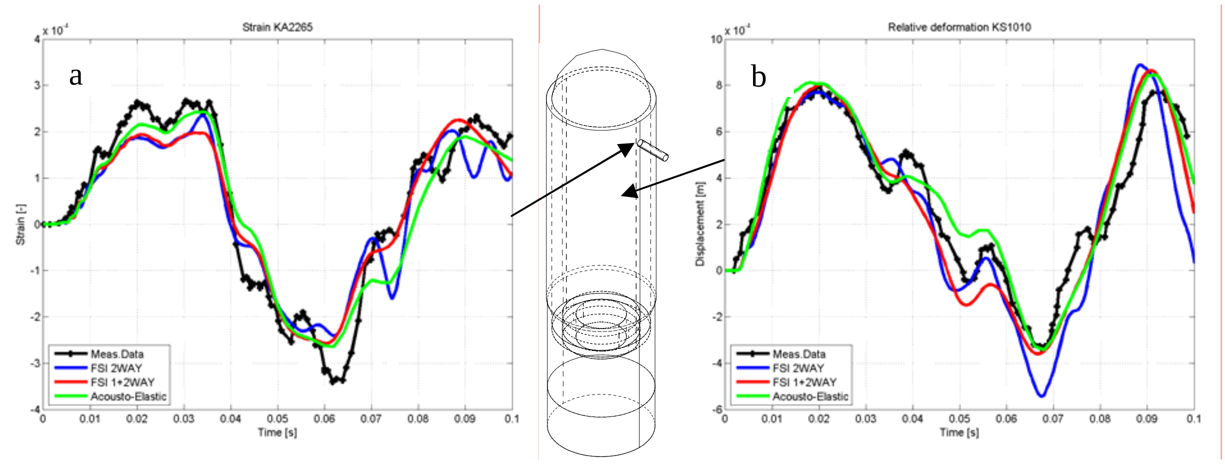

Figure 5. Strain on downcomer wall (a) and relative deformation between core barrel and RPV (b).

The results above shows that the characteristics of the measurement is captured with all three methods. All methods show more or less deviations. From the results above none of the results can be said to be superior to the others. Compared to the original 2 way FSI, the acousto-elastic model runs 100 times faster.

It is obvious that the acousto-elastic method is very attractive due to the computational cost. It should be realized, however, that the HDR geometry incorporates a very small nozzle diameter, compared to a typical BWR or PWR geometry. Hence, the flow velocity in the downcomer is lower than usual which promotes the linear response.

The figure below show the same results as in figure 4, but only for the sequential 1+2 way FSI model. It should be interpreted as follows. The CFD result (blue), without FSI, is run first. The acuosto-elastic result (red) is run afterwards, and the previous CFD pressures are mapped on this model. This is possible because ADINA-FSI can be managed so that only 1-way FSI (mapping of pressure) is performed.

In the beginning the CFD pressure decrease, due to the blowdown, and pulls the structural wall. As a result the structure moves, and the wall now push on the acoustic fluid. Hence, the motion that the blowdown causes results in pressure in the acoustic fluid that imply resistance to this motion. Hence, the CFD and acoustic pressures are, in general, of opposite sign.

The total pressure at the specific location is the sum of these two partial pressures. Simply by adding the two curves the final result is achieved (green). This curve is a duplicate of the red curve in figure 4. The measurement is also shown (black).

The uncoupled pressure waves (blue) are reduced in magnitude and propagation speed, when compared to the measurement. Because of this it has been considered necessary to perform full 2-way FSI coupling to reproduce the HDR V31.1 test, see Wolf (1982) and papers onwards. In Wolf (1982) the effective propagation speed is said to be 40 % of the speed of sound in the water, which seems to be captured well.

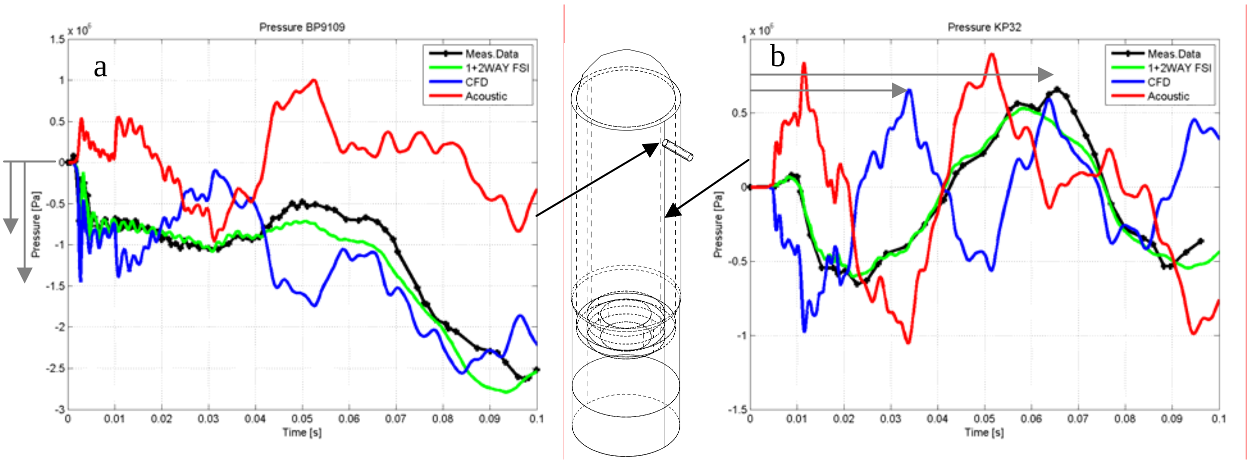

Figure 6. Pressure on downcomer wall (a) and pressure difference across downcomer wall (b).

It may appear surpricing that it is possible to do a sequential FSI computation, since all previous work states that 2-way FSI is a necessity, see Andersson et al (2002), Andersson et al (2003), Sussman and Sundqvist (2003), Timperi et al (2008), and Brandt et al (2008). The 2-way coupling is here done in the FE code, instead of coupling the CFD and FE code.

The explanation is that the HDR V31.1 response is almost linear. Due to the small nozzle diameter, the downcomer velocity becomes small (small drag forces) and that pressure pulses dominate. The actual flow has little influence on the total pressure in the fluid. The pressure waves follow the linear wave equation and the structure is all linear, which validates the use of the linear acousto-elastic model to take care of the 2-way FSI coupling..

Due to the principle of superposition the results can be added, if the model is linear. Thus, if there was no flow at all it would be obvious that the results could be computed separately and that the total results consist of the sum of the partial solutions.

The sequential method is used here to show the FSI effects. It is seen that the pressure in the acoustic fluid is of the same magnitude as the CFD pressure. Hence, the coupling between the structure and the water is strong and for the structural dynamic response a 2-way FSI coupling is necessary. This can also be quantified by comparing the eigenfrequencies for the coupled model and the structure in vacuo.

If a lighter fluid was present, e.g. steam instead of sub-cooled water, the eigenfrequencies would not be significantly affected. It is expected that in that case the acoustic (vibration) pressure would be of much less magnitude than the CFD (blowdown) pressure. It is also common to use sequential 1-way FSI coupling (mapping of pressure) from a CFD model to an uncoupled FE model in the case of steam pipe break in BWR reactors.

Using the acousto-elastic model the eigenfrequencies have been calculated for the structure *in vacuo*, the coupled model, and the fluid itself. The results are shown in table 1.

It can be seen that all eigenfrequences in for the structure and the fluid are greatly affected when they are coupled together, which implies that 2-way FSI coupling is a necessity to capture the dynamic behaviour of the RPV with internals.

Table 1. Calculated eigenfrequencies for the HDR V31.1 problem.

Structure		**Coupled**		**Fluid**	
Mode shape	Frequency Hz	Mode shape	Frequency Hz	Mode shape	Frequency Hz
CB Pendulum	12.0*	Helmholtz	3.0	Helmholtz	3.2
RPV Pendulum	14.3	CB Pendulum	6.5*	Stand. Wave #1	30.2
CB ND3	39.5*	RPV Pendulum	10.6	Stand. Wave #2	50.3
CB ND0	42.2	CB ND3	14.3*	Stand. Wave #3	78.0
RPV ND2	43.5	CB ND2	14.5*	Stand. Wave #4	102
CB ND4	49.1*	CB ND4	21.3*	Etc.	
CB ND2	54.8*	Stand. Wave #1	15.5	Etc.	

In Ludwig and Schumann (1982) the *in vacuo* and coupled eigenfrequencies, as functions of nodal diameter (ND) for the core barrel (CB), are shown. The frequencies marked with an asterisk (*) in table 1 are identified and found to have good agreement with the experiment.

The Helmholtz mode is the mode when the fluid in the nozzle vibrates back and forth (as a mass), whilst the fluid volume acts like a spring, due to its compressibility.

The fundamental structural mode, the pendulum mode of the core barrel, has half the eigenfrequency when coupled to the fluid due to the increased vibrating mass.

The first standing wave mode also reduce its frequency to about the half value, due to the increased flexibility of the boundary of the fluid domain in the coupled case.

The different mode shapes are affected to different extent by the fluid coupling, hence the mode sequence is changed from the *in vacuo* modes.

5 MOVING ON TO APPLIED PROJECTS

The promising ADINA-FSI results in the early 2000s became a starting-point for applied projects of LOCA analyses of BWR and PWR reactors, see figure 7 below. Since 2002 and onwards applied projects have been performed for BWR and PWR reactors. The three methods of HDR V31.1 simulations presented above are performed year 2001, 2006 and 2008.

It is stated in Krieg et al (1977) that due to the small diameter (200 mm) of the break nozzle in the HDR tests, a real blowdown event in a typical PWR (800 mm) results in considerably higher loads. The test conditions were selected to assure a linear structural response (clamped hold down spring and no fuel).The good agreement achieved in the HDR V31.1 simulation is not enough when it comes to LOCA simulation of real PWR and BWR reactors.

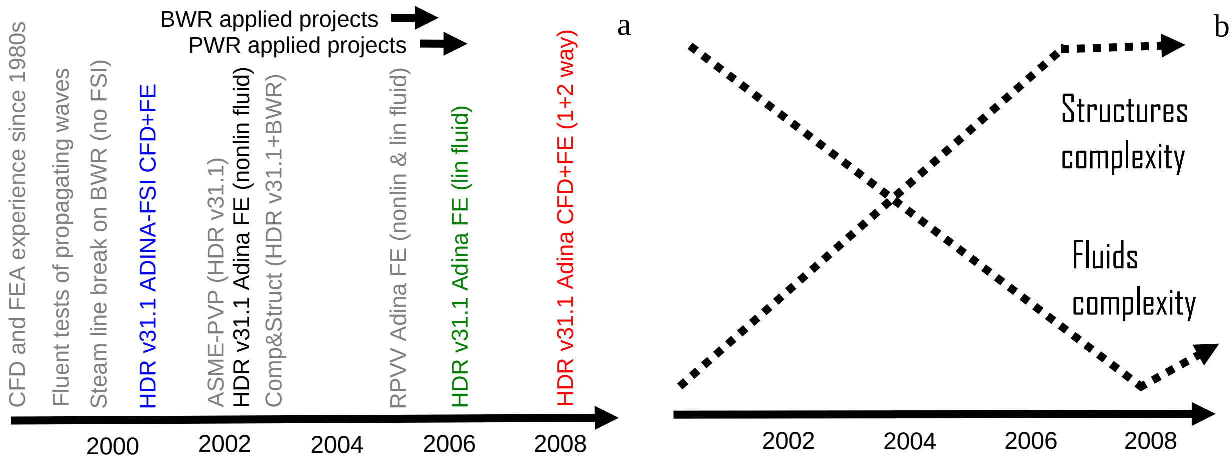

Figure 7. Chronological development of our RPV FSI experience (a), and model complexity (b).

In the beginning ADINA-FSI was used, which was replaced in 2002 by the subsonic potential based fluid in ADINA, see Sussman and Sundqvist (2003). The subsonic model has been the most used method since then, due to its numerical efficiency and ease of use. Since 2005 acousto-elastic models have been used, although not in LOCA analyses first.

The trend has been to use simpler and simpler fluid models. On the contrary, the structural models have had the opposite trend. The linear HDR V31.1 model has developed to very non-linear models, mostly due to contact conditions between internals. The HDR tests were designed for linear structural response, unlike the PWR reactors, see Wolf (1982).

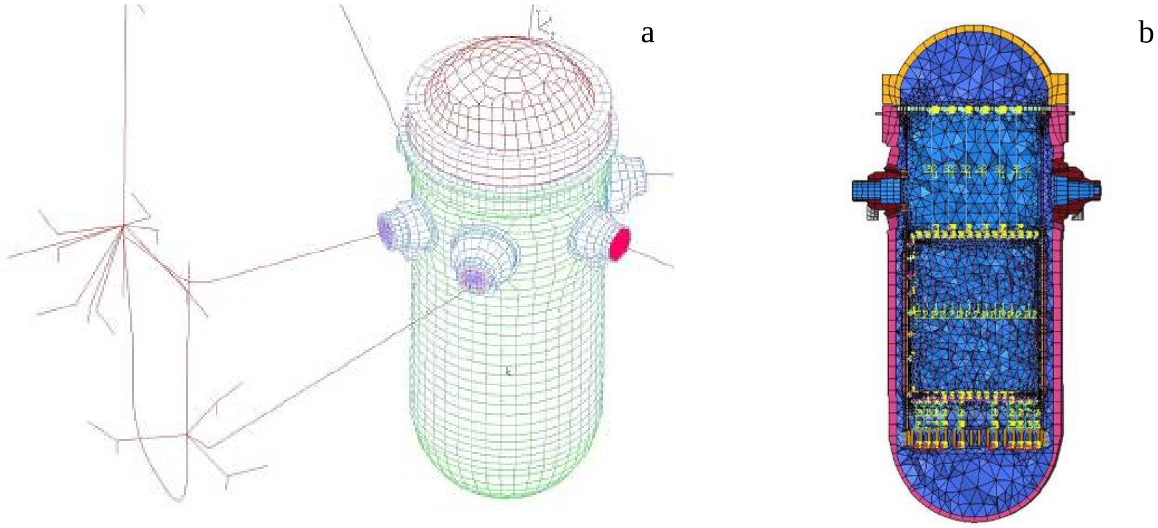

Figure 5. Example model of a PWR reactor with external RCLs (a) and internals with contacts (b).

From the very simple HDR V31.1 simulation the development has led to many numerical tests and insight of where it is possible to simplify.

The following physical phenomena has been incorporated in the applied projects; full or zero pressure, blow-down force on RPV, jet force from pipe end, external pressure build-up, internal flow forces, gravity, pipe release forces, and pipe impact on building.

The following FE modelling issues have been dealt with; FE fluid elements, elements (type, shape, order), simulation time 0.1-4 s, global vibration (GV) load cases (earthquake, etc), non-linear material, contact between internals, fuel structural dynamics, and adding the concrete building.

6 CONCLUSIONS

From the HDR V31.1 validation simulations the following conclusions can be drawn:

We can compute the response of internals, until the sub-cooled fluid reaches the saturation pressure. We can use commercial software and standard computers. The HDR V31.1 test differs from real reactor geometries in an way that promote the use of linear models. We have shown that acceptable results can be obtained with coupled CFD and FE solvers (ADINA-FSI), acousto-elastic and sequential methods. The solver time for the acousto-elastic model is 1/100 of the ADINA-FSI approach.

From the experience from applied projects the following conclusions can be drawn:

The structural integrity is in focus, details in the fluid flow can be neglected. The LOCA load case is one of many load cases when doing an complete analysis of RPV or internals, and the FE model is often used for several purposes. The number of DOFs is typically one order of magnitude higher than the HDR model. Essential structural non-linearities are present during LOCA, therefore the trend has been to use as simple fluid models as possible. The computational cost is of more importance than in R&D activities and therefore size of numerical models and utilized methods are determined on the basis of model economy.

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