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NUMERICAL INVESTIGATIONS ON THE SEVERE LOAD CASES EARTHQUAKE AND TURBINE DISC BURST

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ABSTRACT

For the design process of new power plants as well as for the lifetime extension of existing power plants the consideration of severe loading conditions is an important and challenging task. The ongoing hardware and software development provides comprehensive calculation methods for such assessments. By means of the examples "seismic qualification of an emergency diesel generator (EDG) set" and "consequences of a turbine disc burst" it will be shown how numerical calculations could help understand severe loads and accidents in power plants and if design optimizations are necessary.

For the seismic qualification of an EDG set, the complete mechanical frequency response system comprising the base frame including dampers, the diesel engine, the clutch and the generator, was considered in a Finite Element (FE)-model. Numerical calculations were carried out to qualify the components mentioned above for seismic loads and to define the seismic spectra for the further seismic qualification of attached components like pumps or starting air valves.

Furthermore, the consequences of a turbine disc burst are analyzed by finite element method (FEM). The investigations are focused on the question if broken parts could penetrate the turbine casing and if further consequences have to be considered.

INTRODUCTION

Several severe loading conditions have to be analysed for nuclear power plants. According to the international guidelines, these investigations can be done by analyses, by experiments, by analogy, by plausibility checks or by combination of these types of analysis.

For the two following examples

- "seismic qualification of an emergency diesel generator (EDG) set" and
- "consequences of a turbine disc burst"

experimental testing would be too time consuming and too expensive. Another disadvantage of the experimental investigation is that the importance of parameter variations can hardly be projected in advance. Furthermore, comprehensive and accepted experimental investigations concerning seismic qualification of EDG sets or turbine disc bursts are hardly available. Some of the few data is shown in the following.

- Experimental seismic qualification of EDG sets
  A comprehensive experimental seismic testing program for EDGs was published in [1]. Figure 1 gives an impression of the complexity of the experimental investigation of EDGs using a large scale shaking table.

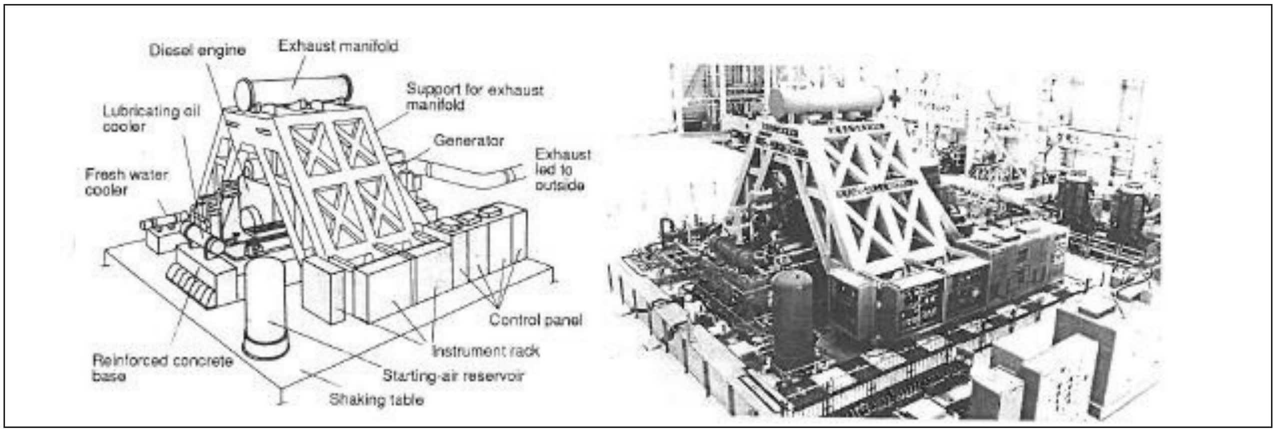

Figure 1: Schematic view and photograph showing arrangement of DG-system test model on (large scale) shaking table (Figure 2-9 and 2-10 in [1])

Although testing details are published in [1], this data is not sufficient for a complete seismic qualification of various EDG sets because of the different EDG characteristics like stiffness, masses, dimensions, dampers etc., which would need to be accounted for.

- Experimental data concerning turbine disc bursts
  Investigating the consequences of turbine disc bursts using experimentation can be quite complex. According to literature on turbines used in aircrafts, it is common to experimentally confirm the resistance of the housing to turbine blade impacts. For impacts caused by turbine disc bursts the testing and qualification of the turbine housing can be complicated because unrealistic large wall thicknesses would be necessary. Furthermore, experimental test data of aircraft turbines is seldom available for reasons of company protected proprietary information
  Concerning the consequences of disc bursts of steam turbines, no experimental data is available but information of real accidents in a coal fired (Duvha Power Station, South Africa) and in a nuclear power plant (Hinkley Point, Sommerset, UK) can be analysed. These accidents caused by overspeed tests or by spontaneous brittle fracture show that not only the thin-walled aircraft turbine housings can be destroyed by the impact of turbine disc bursts or rotor failures but also the housings and the machinery hall of steam turbines in power plants can fail.

The factors mentioned above show that severe load cases could not be analysed experimentally in an acceptable time schedule and it would be time consuming to consider several parameter variations. For such investigations state of the art numerical analyses are presented in the following.

NUMERICAL ANALYSIS OF AN EDG SET FOR SEISMIC LOADS

Workflow

According to the workflow shown in Figure 2, first of all, the safety related tasks have to be defined. The safety related tasks are load-carrying capacity, integrity and/or functionality. The functionality of the EDG system is a safety related task because each nuclear power plant requires emergency power for safe shut down systems if e.g. serious reactor accidents or the loss of off-site power during or after earthquakes occurs.

For some components of the EDG like fuel oil tanks, piping or exhaust silencers, functionality is similar to the safety related task integrity. For the base frame, only the load-carrying capacity has to be qualified.

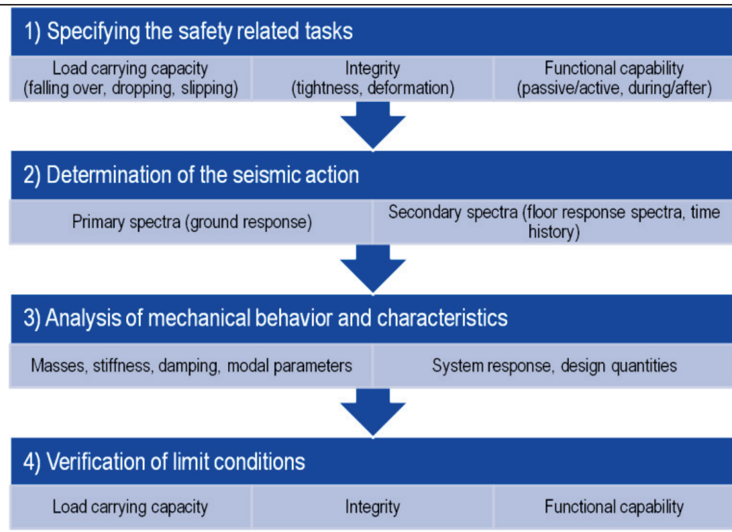

Figure 2: Workflow Seismic Qualification according to [2]

In a second step, the seismic loads must be defined. The calculation of the floor response spectra - secondary spectra – is based on the ground spectra – primary spectra – and the soil-building-interaction.

The most complex part for the seismic qualification of EDGs is the analysis of the mechanical behaviour and characteristics. To make sure that the results are conservative and realistic as possible, the FEM model of the EDG must consider the mass and stiffness of all relevant components like the diesel-engine, clamp, generator, base frame, springs and damper systems. To keep the FEM model as simple as possible, components fixed on the base frame, on the generator or on the diesel engine, that do not have an influence on the seismic behaviour of the mechanical main system, are not be considered in the FEM model. These components will be analysed separately by comparing the allowable accelerations and the accelerations resulting from the seismic FEM calculations. Experimental qualifications for small components like starting air valves, which cover quite high accelerations over a wide range of frequencies, are often available.

According to the last step of the workflow in Figure 2 it has to be checked if the requirements concerning load-carrying capacity, integrity and functional capability are fulfilled. For the components considered in the FEM model the stresses and deformations can be analysed as a result of the calculations. For components fixed on the base frame, on the generator or on the diesel engine, but without influence on the seismic behaviour, the maximum acceleration can be compared to accelerations used for the experimental component qualifications.

Safety Related Task

EDGs are active systems and must secure the power for safe shut downs during and after earthquakes because off-site power can be lost. As mentioned above, therefore the functionality is the safety related task for EDG systems.

Seismic Action

Based on the primary spectra – ground acceleration – and the soil/building-structure/interaction, the floor response spectrum will be generated. The primary spectra are the input for FEM models covering the building structure. In Figure 3 an example of a FEM model of an EDG building structure is shown with its corresponding hexahedron mesh.

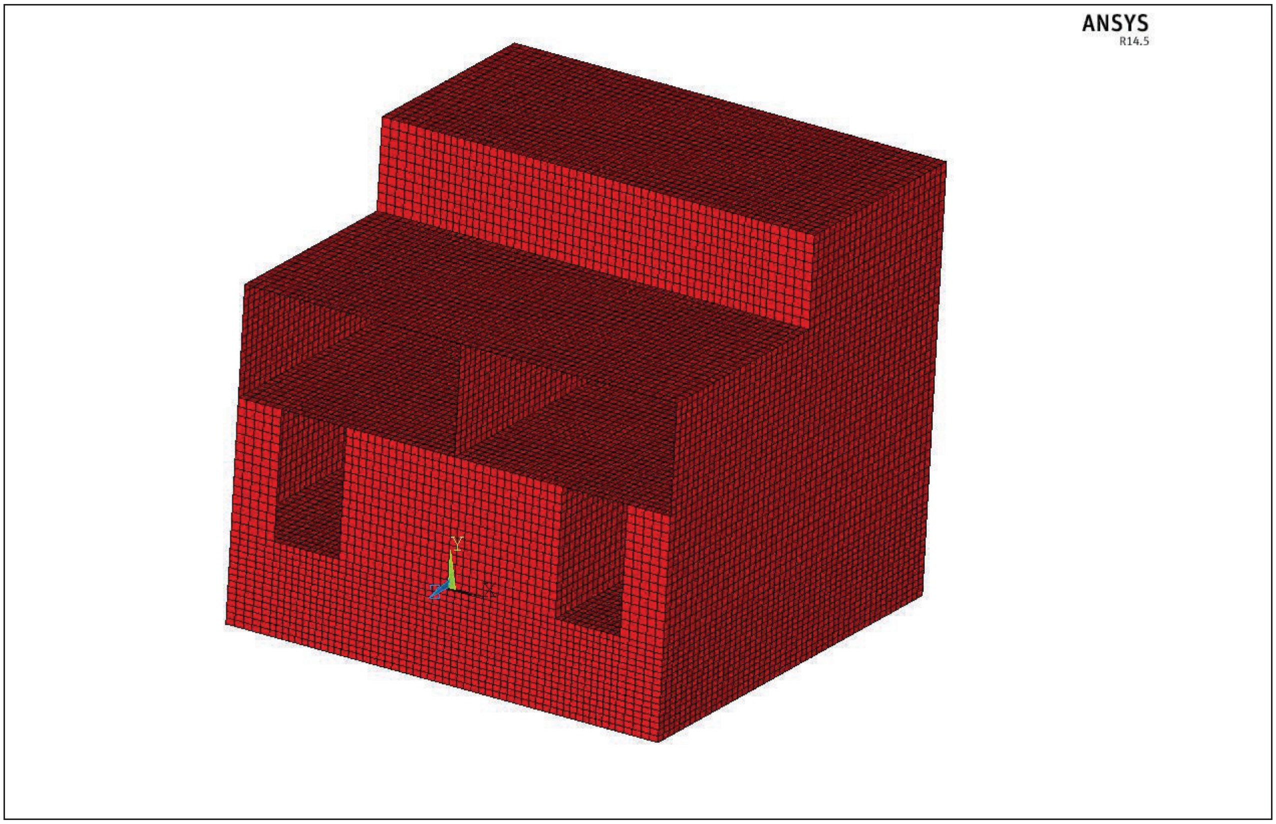

Figure 3: FEM model, EDG building structure

With the soil/building-structure/interaction-calculation the response accelerations of each floor could be determined. An example of 2 typical floor response spectra for EGDs (results of soil/building-structure/interaction-calculation) at sites with relatively high seismic accelerations is shown in Figure 4. Also in Figure 4 the valve requirements and the accelerations of a valve test are shown.

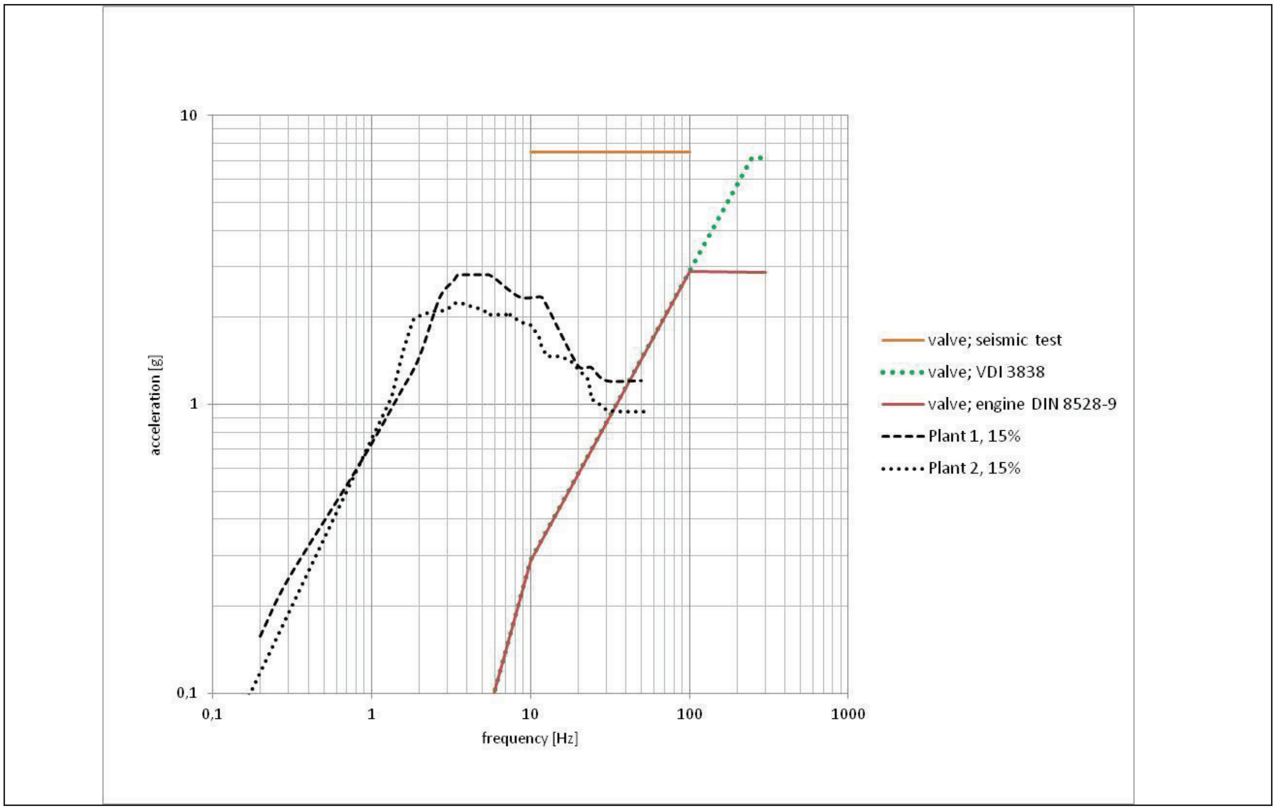

Figure 4: EDG floor response spectra for 2 European nuclear power plants with relatively high seismic loads and valve requirements

Mechanical Behaviour

In order to analyse the mechanical behaviour of an EDG set, the FEM model must be as realistic as necessary but as simple as possible. Therefore, the stiffness and mass distribution of the main load-carrying components like base frame, springs and damper, diesel engine, clamp and generator including the generator shaft must be as realistic as possible. Details like cylinders and crankshaft of the diesel engine need not be modelled for the seismic analysis because the seismic loads are not critical loads in these components.

Importing the manufacturer's component CAD database in the FEM program is avoided because the manufacturers use different CAD programs and the CAD database includes a lot of details, which are relevant for the manufacturing process, but not for the seismic analysis. Figure 5 shows a FEM model of an EDG set with a sufficient detail and adequate meshing for seismic analysis. The model is prepared in a parametric way so that the main dimensions can be adapted to other EDG sets.

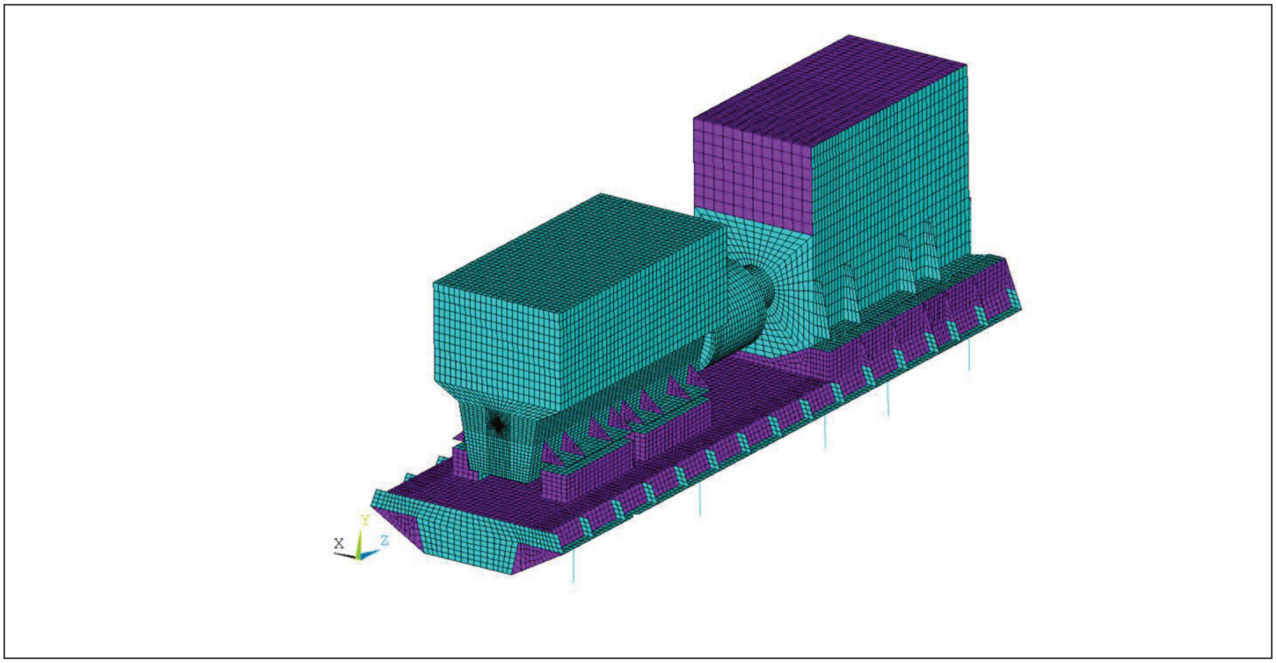

Figure 5: EDG FEM model

The eigenfrequencies and the corresponding modal masses (percentage of the total mass) are the important results. Relevant for further investigations are these main eigenfrequencies. For each principle direction the sum of the modal masses should be equal to the total weight of the EDG set. As shown in Figure 6 the first eigenfrequencies are below 10 Hz and within the acceleration plateau. According to our experience the effective masses of the first horizontal modes cover approximately 60% of the total mass and the effective mass of the first vertical mode is about 100% o the total mass of the EDG.

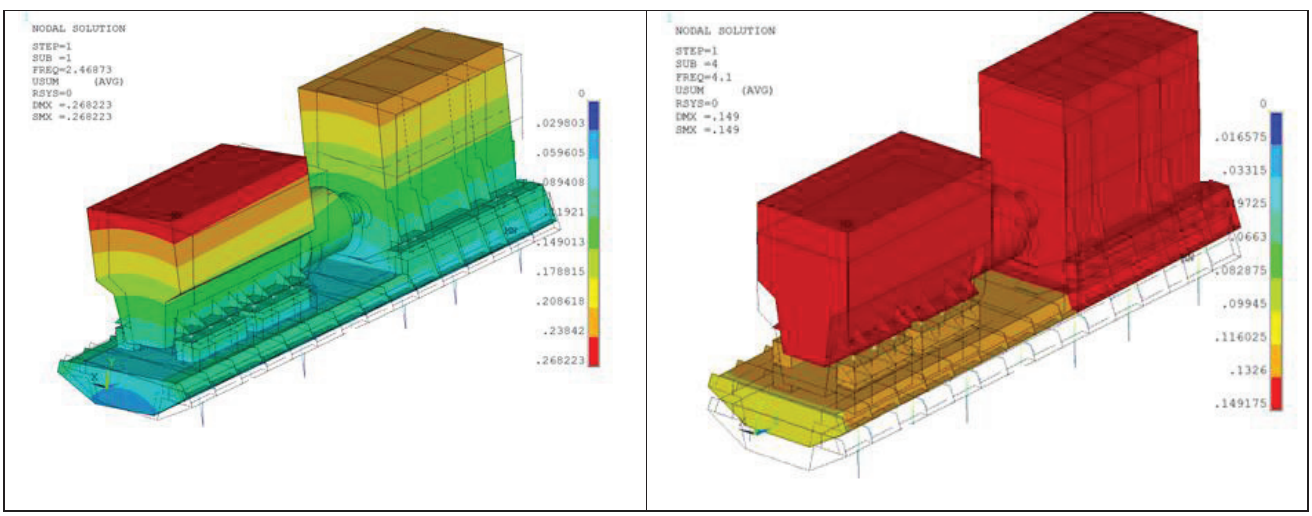

Figure 6: EDG first eigenfrequencies (2.5 Hz horizontal, 4.1 Hz vertical) and corresponding displacements (0.268 mm and 0.149 mm)

Verification Of Limit Conditions

As mentioned above for the eigenfrequencies with the main modal masses should be checked if they are within the plateau of the seismic spectrum. Depending on the evaluation, weather the resulting stresses and deformations are acceptable, it can be judged if design changes are necessary or not. Sometimes it could be necessary to change the characteristics of dampers and springs. In general, the primary stresses should not exceed the yield strength of the components because it can be assumed that the corresponding deformations of the EDG main components are within the acceptable limits for functionality. Furthermore, the elastic deformations (deflection and torsion) at the clamp and the generator shaft should be compared to the acceptable limits. All stresses and deformations must fall within the manufacturer's guidelines and design limit requirements.

Other important results include the main response accelerations of the frame, the engine and the generator in each principle directions. The maximum response acceleration can be determined by a quadratic combination of the three directions. This result can be used for the experimental verification of components which are fixed on the frame, the engine or on the generator. For example, typical valve requirements are shown in the spectra in Figure 3. The results of successful experimental testing of valves are also shown on Figure 3. It is obvious that the accelerations of the experimental seismic valve qualification cover the typical requirements according to the guidelines and the main response accelerations of EDG seismic analysis.

Numerical Analysis Of Turbine Disc Bursts

Analytical and numerical containment solutions

Important energy based solutions for the analysis of impacts caused by disc bursts fragments are published in [3]. A numerical study concerning the impacts of turbine disc bursts is given in [4]. According to [4], the numerical results show a good correlation to the date published in [3]. The results discussed in [3] and [4] are focused on the design method for the containment enclosing the centrifugal rotor tests, which are commonly carried out by turbomachinery manufacturers. These results provide a good basis of comparison for the following turbine housing impact analysis.

Impact analysis of turbine housings

The turbine housings are often made up of several shells. This has to be considered in the FEM model because each of the separate shells is able to absorb a percentage of the kinetic energy of the disc fragment by elastic and plastic deformation. A typical turbine housing geometry is shown in Figure 7.

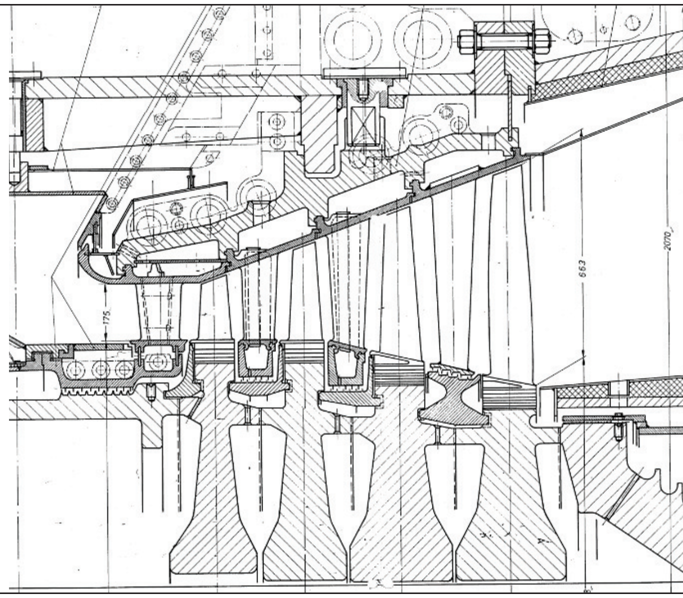

Figure 7: Turbine housing design (example drawing)

For the impact analysis of the turbine housing, the explicit FEM program Ls-Dyna was used. According to the assumptions in [3] and [4] concerning the bursting event, a 90° disc fragment including the blades was used for the analysis, see Figure 8.

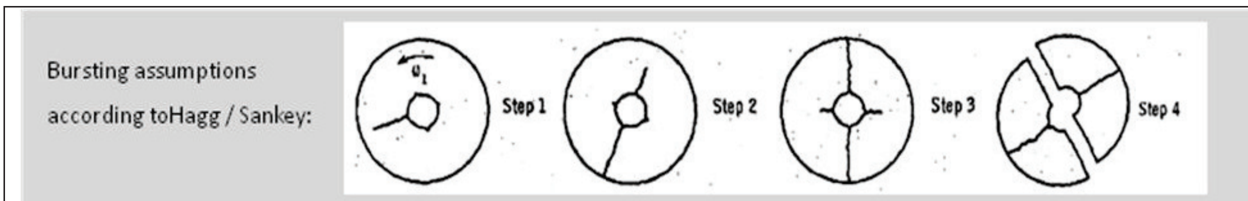

Figure 8: Bursting assumptions: disc is breaking in 90° fragments [3]

For the parametric FEM model, a maximum of three shells was considered for the turbine housing. Other parameters of the FEM model are diameter, wall thickness, cone angle and circumferential angle of the shells and the circumferential angle of the disc fragment. Considering these geometrical parameters, it is possible to modify the FEM model to represent other typical turbine housing and disc burst configurations. For the geometry configuration shown in Figure 7 the FEM model shown in Figure 9 was developed.

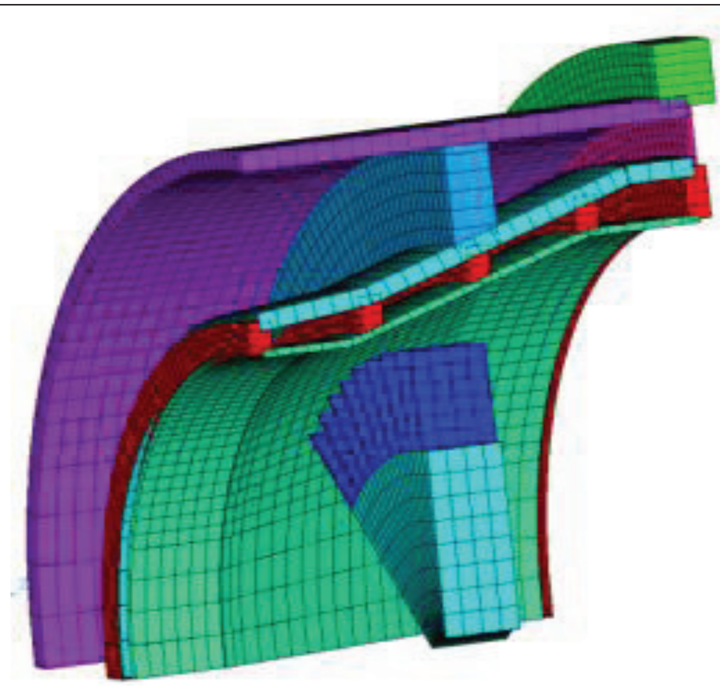

Figure 9: FEM model, turbine housing and disc fragment

For the impact analysis of turbine disc bursts the modified piecewise-linear plasticity material model with enhanced failure criteria - including effective plastic strain, plastic thinning and major in-plane strain - was used. This material model considers the true stress/effective strain curves for given strain rates. Figure 10 shows the Ls-Dyna simulation results for the case with an initial turbine disc burst velocity corresponding to a nominal rotational turbine rotation speed of 3000 rpm. For this burst velocity the inner shells are penetrated and the outer shell shows high deformations, but no penetration.

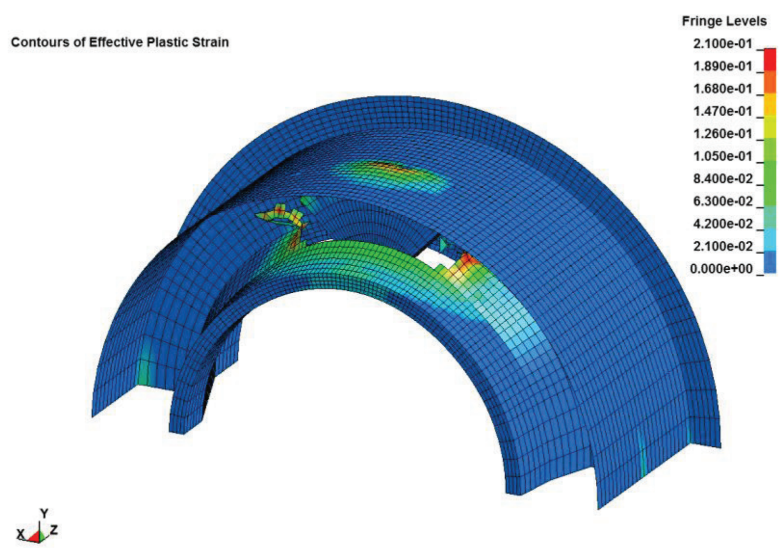

Figure 10: FEM model, turbine housing and disc fragment, effective plastic strain [-]

The results can be analysed with regard to the extent of shell penetration. If the probability of shell penetration to the turbine surroundings is unacceptable the model computation can be repeated until a design, which ensures suitable safety margins (low probability for turbine housing disc breach and or turbine disc fragment penetration), is found.

CONCLUSION AND OUTLOOK

The examples presented in the paper show that a numerical analysis of severe load cases is essential in the planning, upgrading or requalification process of nuclear power plants because several parameter studies are necessary for a comprehensive evaluation.

With adequate experience (including experimental and numerical experience from several industries) it can be interpreted if the numerical results are conservative and how close they are to reality. The numerical analysis is essential for understanding and evaluating the consequences of severe load cases because only very few results of large scale experiments are available.

It should be noted that not only the nuclear industry but also other industries use this method of numerical analyse in order to analyse severe accidents if large scale experiments are not possible or too time consuming. For example, for offshore wind parks in the German North Sea numerical simulations of the collisions of ships (oil-tanker) and wind turbines are common to investigate possible pollution of the environment, see [5]. The developments show that also the consequences of other severe accidents like chemical explosions, pipe ruptures or airplane crashes could be analysed numerically in an appropriated time schedule.

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