

Structural Integrity Assessment of a Rupture Disc Housing with Explicit FE-Simulation

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1 ABSTRACT

Structural integrity of reactor components is most generally proven based on stress calculation without or with limited plastic deformation. Dynamic problems may often conservatively be verified with load factors on quasi-static calculations. However dynamic and highly nonlinear explicit Finite-Element (FE)-simulation may give a deeper insight to a physical problem or may be useful if a conservative approach cannot be easily made. Therefore it can give an important contribution to the assessment of safety aspects in case of large deformations and short time dynamic loads during faulted or emergency plant conditions. In this paper, the impact-simulation for a rupture disc housing is taken as an example to discuss safety factors complying with current regulations and to describe sources of conservatism depending on the level of detail of the idealisation.

2 INTRODUCTION

Low pressure turbines of PWR power plants are generally equipped with rupture discs to avoid a pressure overload that could lead to a damage of the turbine and the condenser.

To avoid an intake of air in case of a defect or imploded rupture disc membrane, a freely supported plate in the rupture disc housing withstands the vacuum forces. In case of a rupture disc burst caused by an excess pressure in the turbine, the plate is accelerated and impacts the retaining clamps mounted on the housing.

The aim of the investigation is to assure the structural integrity of the rupture disc housing in compliance with essential safety standards. Moreover the calculations are taken as an example to discuss general aspects and safety margins for short time dynamic and impact simulation.

The calculations described here have been carried out with LS-Dyna based on explicit time integration. Beside a purely Lagrangian calculation an arbitrary Lagrange Eulerian (ALE) approach to capture the fluid structure interaction, as e.g. used in the automotive industry for airbag inflation simulation, has been tested. Further applications for explicit FE-simulation related to nuclear energy safety concerns can be found e.g. for dropped load impact, plane crash, explosion shock waves and container (spent fuel cask) certification. Also for postulated pipe breaks the dynamic effects on the neighbouring systems may be simulated

3 IMPACT SIMULATION

Explicit FE-simulation with LS-Dyna has been carried out to capture the nonlinear and short time dynamic loading scenario. In the following actual stress and strain values are not depicted. The simulation predominantly is used as an example to discuss calculation methods and safety margins.

3.1 FE-Model

Model Description

Figure 1 shows the geometry of the rupture disk housing. After the burst of the rupture disk membrane (1) the outtake of steam accelerates the plate (2) that impacts the clamps (5). The full geometry of the housing has been modelled to assess different unsymmetric impact conditions. The clamps and the housing ring (4) are modelled with solid elements; the rupture disk membrane, plate and the cylindrical part of the housing are modelled with shell elements. The screws (3) attaching the clamps to the housing-ring are modelled simplified as solid head and bolt tied to the ring. Pre-stress at the bolts is applied via the *INITIAL_STRESS_SECTION [1] keyword.

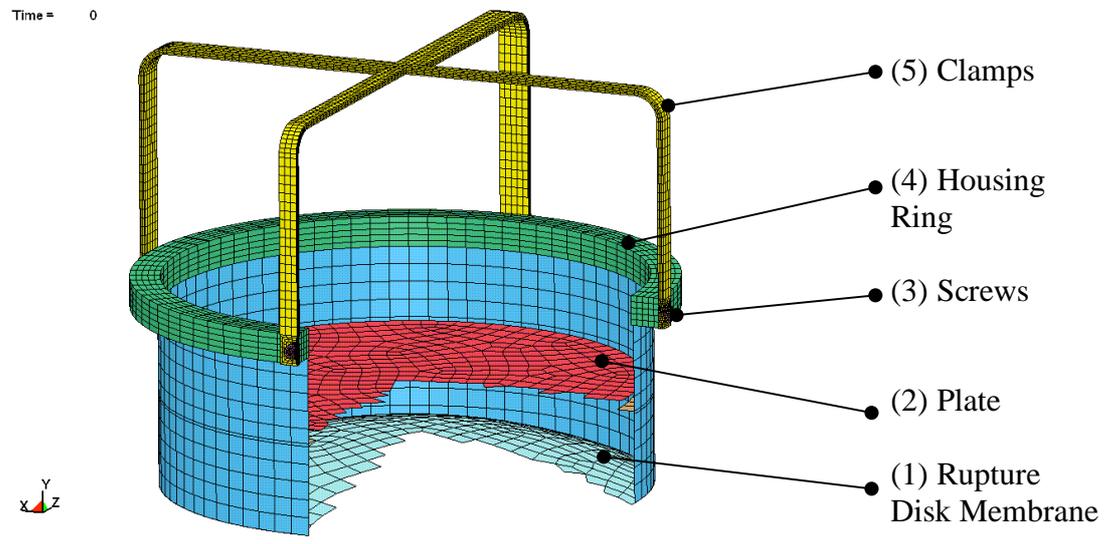


Figure 1. FE-Model of the rupture disk housing

Material Modelling

For the clamp material the isotropic elastic-plastic, rate dependent material model *MAT_124 (*MAT_PLASTICITY_COMPRESSION_TENSION) has been used. For *MAT_124 different true stress vs. logarithmic plastic strain curves may be applied for tension and compression. As typically used for metallic parts, the elastic-plastic material model *MAT_24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) with arbitrary stress versus strain curves and arbitrary strain rate dependency has been used for all other parts of the structure. In order to account for necking, material degradation and damage may be induced via the plasticity load curves by reducing the stress when uniform strain is exceeded.

Minimum material strength values have been applied for the clamps. For the impacting plate mean material strength data has been used, as minimum values may potentially be non-conservative.

3.2 Impact Simulation - Lagrange

For the purely Lagrangian impact simulation an initial velocity has been applied to the plate. Beside an impact position with a zero horizontal angle an arbitrary initial angle position of the plate before the impact has been investigated. A constant pressure is applied to the plate during the impact, to account for the impulse of the steam flow.

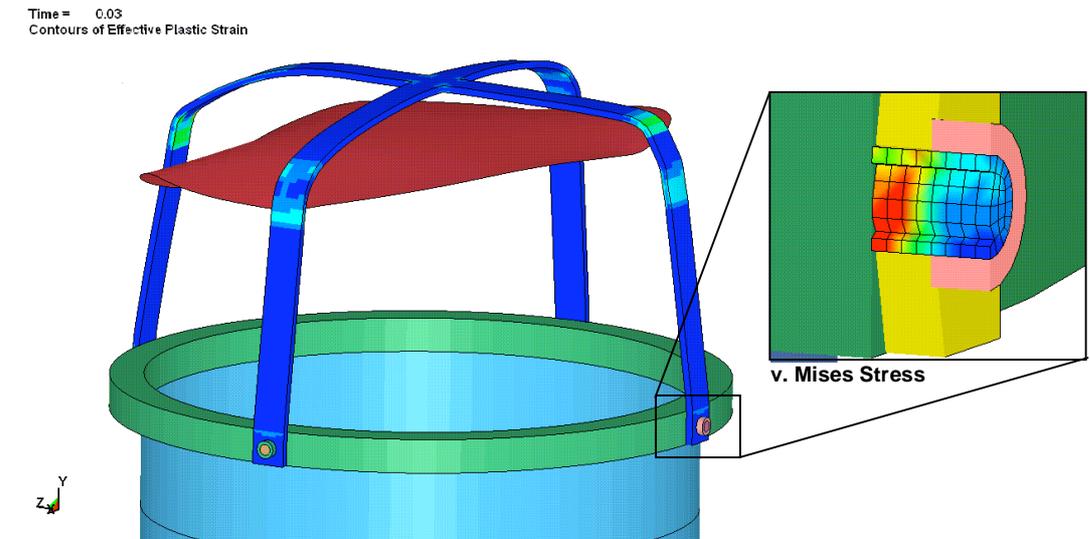


Figure 2. Deformed shape after impact – plastic strains at the clamps and stress in the screw at max. loading

Simulation Results

Maximum plastic deformation occurs at the arcs of the clamps and at the drill holes. For the nominal burst conditions the minimum failure strain is not exceeded.

The maximum stresses at the screws calculated by section forces or directly taken from the stress output are compared to the maximum allowable stresses. In this case for nominal burst conditions, the screws are not predicted to fail.

3.3 Impact Simulation - ALE

The impact velocity of the plate may conservatively be determined by basic equations. The precise prediction of velocity and impact position of the plate underlies an uncertainty depending on the conditions of the membrane burst and the steam flow.

The dynamic effects of the steam flow can be simulated using the ALE capability within LS-Dyna. Thus the applicability of basic formulas may be verified and parameters as steam flow velocity vector and burst initiation may be varied. In our simulation the thermodynamic state of the steam is defined by the equation of state `*EOS_IDEAL_GAS` together with the material card `*MAT_NULL`. The `*BOUNDARY_AMBIENT_EOS` has been used for ‘reservoir’ elements to predetermine the thermodynamic state inside the turbine throughout the simulation time. The outflow velocity can be controlled by a function for the `*BOUNDARY_PRESCRIBED_MOTION` card. As a simplification the air above the membrane is modelled as `*INITIAL_VOID`. The mass of the steam is transported from element to element in the fixed Eulerian mesh and the contact to the structure is defined by `*CONSTRAINED_LAGRANGE_IN_SOLID`, in this case penalty based with erosion.

Simulation Results

Figure 3 shows the ALE simulation during the membrane burst. Figure 4 shows the acceleration of the plate. With the velocity vectors in Figure 4 it can be seen that the boundary conditions of the ALE mesh allow an outflow of steam above the housing ring. Due to the dynamic effects, the fluid structure interaction force curve partly exceeds the value calculated by the area and the nominal density and velocity.

Time = 0.012

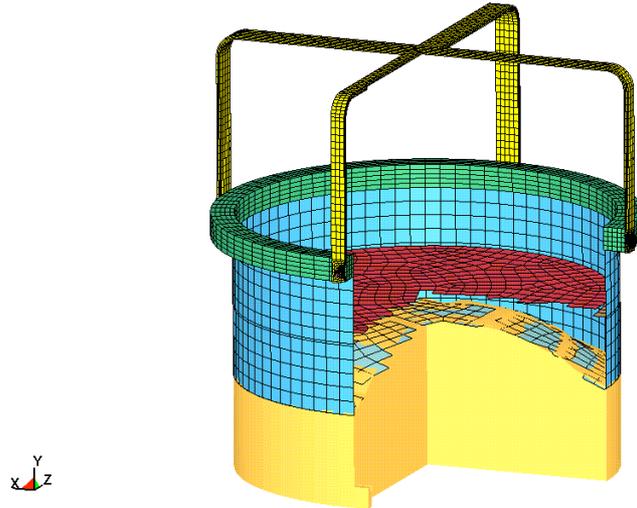


Figure 3. Burst of the Membrane.

Time = 0.039
Vector of Total-velocity

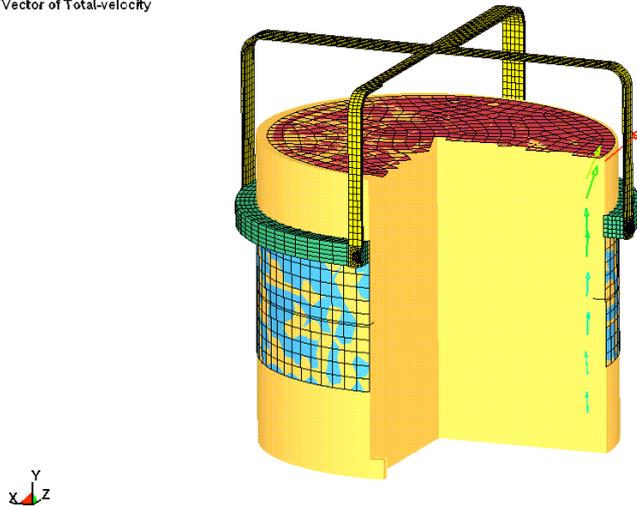


Figure 4. Acceleration of the plate after membrane burst – velocity vectors of the fluid.

Figure 5 shows the deformed state after the impact of the plate. Contours of plastic strain are applied to the clamps. In our simulation a vertical velocity vector for the steam flow without spin and a homogenous failure of the membrane has been assumed. Thus the impact angle of the plate is small.

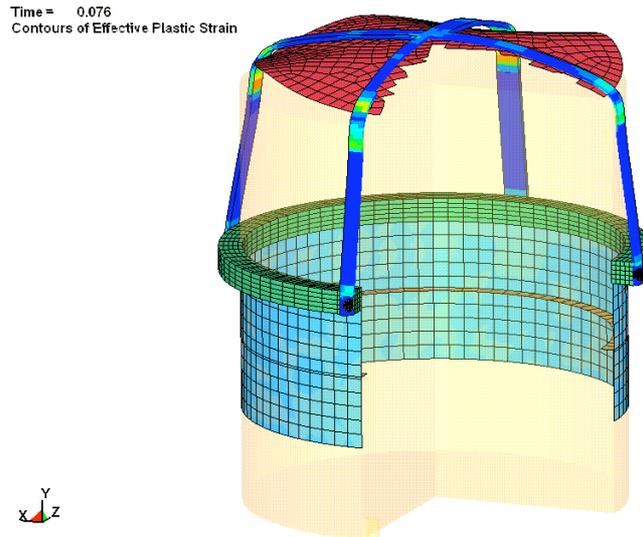


Figure 5. Deformed shape after impact – plastic strains at the clamps

4 SAFETY MARGINS

Generally safety factors have to be applied or a strain criterion has to be met in order to account for the uncertainties of a simulation. For the described loading scenario the following uncertainties may lead to an inaccuracy of the predicted results:

- deviation of material properties
- manufacturing tolerance, manufacturing defects
- flow boundary conditions and parameters
- ..

For the rupture disk housing potential defects might occur at the following locations:

Clamps (arcs and drill holes):

Rupture of the clamps is induced if the plastic failure strain is exceeded. Generally a failure strain criterion should account for triaxiality, because for specific load cases and geometries failure may occur due to a hydrostatic spall pressure without exceeding the uniaxial quasi-static failure strain. So it generally has to be checked if the available plastic failure strain value is valid for an acceptance criterion to prove the structural integrity. Also it should be noticed that failure strains in material standards are generally conservative and do not account for local phenomena as necking etc.

Screws:

In this case failure of the screws is assumed, when a maximum allowable bolt-stress is exceeded. For scenarios, where the early failure of fasteners is not conservative, failure loads have to be mean or maximum values.

Adequate safety factors have to account for the underlying uncertainties, but can hardly be found for short time dynamic calculations in the current literature. Requirements and safety factors for limit load calculations are provided in the German safety standards KTA 3201.2 [2] and KTA 3204 [3]. Also ASME III [4], ASME VIII-2 [5] and EN 13445-3 [6] provide requirements for limit load calculations. For explicit dynamic simulations the safety factors for limit load calculations seem to be the most applicable in the current regulations.

The different safety standards partly have varying requirements for plastic collapse calculations based on the limit load method and elastic-plastic stress analysis method, for instance regarding the prescribed flow rules (v. Mises or Tresca), material laws for plasticity (ideal plastic or true stress-strain curve) and the analysis

types (considering large deflections or not). Moreover the regulations contain partly varying rules to determine yield stresses and safety factors for the relevant service levels.

According to KTA 3201.2 [2] and 3204 [3] an elastic-ideal-plastic material law is applied for limit load calculations with the yield stress and the safety factor depending on the operating condition. Nevertheless for specific load cases in explicit dynamic simulations a conservative elastic-ideal-plastic material curve may lead to an unrealistic overall response of the structure. Also minimum material values are not necessarily conservative if e.g. applied for impactors. In ASME VIII-2 [5] true stress vs. strain curves are applied for large deflection analyses with a safety factor of 2,4 for design load cases.

If structural parts simply have to withstand a dynamic load regardless of the residual deformation, a service level D safety margin for a calculation with a conservative realistic material stress-strain curve appears to be valid. Taking into account the different requirements for Plastic Collapse simulations a safety factor of 1,5 on the relevant load appears adequate to prove the integrity of structural parts (except screws) at short time dynamic loading. The proposed load factor on the relevant load corresponds to a factor on the introduced energy to be absorbed by the system.

5 CONCLUSION

Different approaches to apply safety factors for explicit dynamic calculations are possible. In order to comply with current safety standards, it is suggested that for the proof of structural integrity by explicit dynamic calculations, a safety factor on the relevant load related to plastic collapse calculations is proposed. Another possibility for an acceptance criterion is a safety margin on the plastic failure strain, but this is currently not found in safety standards for nuclear applications.

For the Lagrangian rupture disk burst simulation the suggested safety factor is 1,5 on the enveloping initial velocity. An idealisation of the physical problem comprising fluid-structure interaction may help to validate the applicability of analytical formula and may lead to less conservatism of the predicted results. Currently the verification of analysis parameters for the ALE simulation is not completed. Nevertheless a safety factor of 1,5 on the differential burst pressure in a coupled fluid-structure simulation leads to a reduced load at the clamps compared to increasing the velocity of the plate by 1,5.

REFERENCES

- [1] LS-Dyna Keyword User's Manual, Version 971
Livermore Software Technology Corporation, May 2007

- [2] Kerntechnischer Ausschuss
Sicherheitstechnische Regel KTA 3201.2
Komponenten des Primärkreises von Leichtwasserreaktoren
Teil 2: Auslegung, Konstruktion und Berechnung
In der Fassung von Juni 1996
(BAnz. Nr. 216 vom 19. Nov. 1996)

- [3] Kerntechnischer Ausschuss
Sicherheitstechnische Regel KTA 3204
Reaktordruckbehälter-Einbauten
In der Fassung vom November 2007

- [4] The American Society of Mechanical Engineers
ASME Boiler & Pressure Vessel Code, Section III
Rules for Construction of Nuclear Power Plant Components, Division 1
2008a Edition

- [5] The American Society of Mechanical Engineers
ASME Boiler & Pressure Vessel Code, Section VIII
Alternative Rules, Division 2
2008a Edition

- [6] Deutsches Institut für Normung e.V.
DIN EN 13445
Unbefeuerte Druckbehälter
Teil 3: Konstruktion
Deutsche Fassung EN 13445-3:2002
Berlin: Beuth Verlag, November 2003