Assessment Strategy of Numerical Analyses of RAM Package Components – 14619

Lars Mueller *, Olaf Schilling **, Viktor Ballheimer *, Frank Wille *, Steffen Komann *
* BAM Federal Institute for Materials Research and Testing
** TÜV Rheinland, Industrial Services GmbH

ABSTRACT

In Germany current package design safety cases include more and more advanced numerical methods, e. g. finite element analysis (FEA), often in combination with local concepts of strength evaluation of the structure. This approach requires extensive modeling and verification procedures. As a consequence the efforts of authority assessment of design safety analysis increase as well. Only the check of pre- and post-data of numerical calculations is often not sufficient for the safety assessment. On the other hand own analyses of the mechanical problem by performing an independent numerical modeling and analyzing is not always realizable. Therefore it is necessary to look for optimized procedures of the assessment, without loss of safety. This paper shows possibilities for the assessment strategy of numerical analyses with focus on simple analytical approaches as comparative calculations. Such approaches can be helpful to support evaluation of numerical calculations in the whole assessment procedure.

Three examples are considered to show which possibilities and limits exist to support the assessment of numerical analyses using analytical comparative calculations. Two examples of bolt and lid analysis show the influence of component and boundary stiffness on the results. Thickness to length/width ratios are partially exceeded and only fixed or free boundary conditions can be analyzed analytical. Nevertheless these analytical approaches can help to evaluate the numerical results for the assessment. The example of a trunnion demonstrates the limits of analytical approaches. The trunnion shows a complex deformation behavior and local stresses. A single basic theory isn’t matching and a construct of several approaches is not useable for calculations of local stresses. Therefore numerical calculations during assessment are necessary. Analytical approaches are not always purposeful but often effective to reduce the effort of assessment for numerical analysis of complex and safety relevant components of RAM packages.

INTRODUCTION

The transport of packages for radioactive materials is regulated according national and international safety requirements. The compliance with the regulations shall be accomplished by one of the following approaches or a combination of these [1]:

performance of tests with specimens, with prototypes or samples of the packaging; reference to previous satisfactory demonstrations of a sufficiently similar nature; performance of tests with models of appropriate scale; calculation or reasoned argument, when the calculation procedures and parameters are generally agreed to be reliable or conservative. The safety analysis of the package design has to be documented by the applicant in the package design safety report (PDSR).

Current package design safety cases provided by applicants include advanced numerical methods, e.g. finite element analysis (FEA), often in combination with concepts of local strength evaluation of the structure which normally requires extensive modeling and verification procedures. As a consequence the efforts of competent authority for the assessment of design safety analysis performed by the applicant increase as well. Only the review of pre and post data of numerical calculations is not sufficient for an assessment of analysis results. On the other hand an independent analysis of a mechanical problem by using a complete independent numerical model is not always realizable.

In this paper some questions regarding mechanical design assessment are discussed with focus on the possibilities and limitations of analytical approaches. Such approaches can be helpful to support evaluation of numerical calculations.

DESIGN AND ASSESSMENT STRATEGIES

Design and assessment strategies for packages of radioactive material are not specified in detail and differ with respect to each package type. The objective is to guarantee the compliance of the package with the regulatory requirements [1]. A global structure for the PDSR (safety case documentation by the applicant) is provided by the European guideline [4]. But specific analyses and safety cases are not defined in this document. Therefore BAM prepared specific guidelines to explain and define detailed support and requirements for the package design safety analyses in Germany. The guideline BAM-GGR 008 [5] should be used for numerical analyses; BAM-GGR 012 [7] describes approaches for bolted lid and load attachment systems.

In general the properties of each packages component and its safety related requirements define the scope of analysis in design and assessment phases.

Component properties

The mechanical behavior of a package component is defined by its geometrical shape, material properties, applied static or dynamic loads and type of fastening to basic structure (boundary conditions). The properties mentioned may be of simple up to complex nature as described in the following table.

TABLE I. Component and load properties (with typical examples)

Properties	Simple	Complex
Geometry	can be idealized as bars, plates or shells (closing plate)	bodies of complex shape (trunnions)
Material	assumed as linear elastic or ideal plastic behavior (bolts)	non-linear behavior with hardening, strain rate effects, creeping (gasket)
Load-time characteristic	assumed as static or quasi-static loads (crane operation)	complex dynamic characteristic (1 m puncture bar drop test)
Load application	idealized as point-, line- or surface load (internal pressure)	changing contact load like bearings (trunnion)
Boundary conditions	can be idealized as fixed or hinged connection of separate component (welded lid)	separation from basic structure is not reasonable, system of components (bolted lid)

Table I shows, how the complexity of analysis depends on the mechanical properties and the loading conditions of the component. Simple components can often be calculated analytically. The mechanical behavior of complex components and systems can analyzed reliably only by numerical models.

Component safety

In addition to the component properties, also the safety related requirements which depend on safety objectives and the corresponding degree of utilization define the effort of design analyzes and assessment work.

In Germany the guideline BAM-GGR 011 [6] is used for classification of safety relevant requirements. Therein three grades of packaging components are specified:

- Grade 1: components, which ensure directly the safety objectives
- Grade 2: components, which ensure indirectly the safety objectives
- Grade 3: all other components

This classification can be restricted on sections, features or manufacturing phases of a component. The highest safety relevance of a component is decisive for the component classification. The classification grade of each component is defined in the parts list of the package.

Experience by BAM shows that the analysis depth increases with a higher safety relevance of the component as follows:

- Grade 3: less effort to the analysis approach, simplified approaches
- Grade 2: analytical calculations acceptable if applicable (nominal stresses)
- Grade 1: precise analysis methods usually required (FEM, local or nominal stresses)

In general the degree of component utilization has an additional influence on design and assessment. The effort for analyses increases with higher degree of utilization. So the degree of utilization can be seen as reduction factor on the effort of design and assessment.

Effort of design and assessment strategies

Computational programs and computer technology are constantly developing. Numerical investigations of the realistic behavior of complex components are becoming increasingly possible, which so far could only been studied experimentally. Therefore such numerical calculations are to be provided in the context of cask design according to the state of the art. Thus these calculations are to be assessed by the competent authority.

The following diagram (Fig. 1) shows the influence of component complexity and safety requirements (depending on classification grade) on the effort for the design of packages and the corresponding safety assessment.

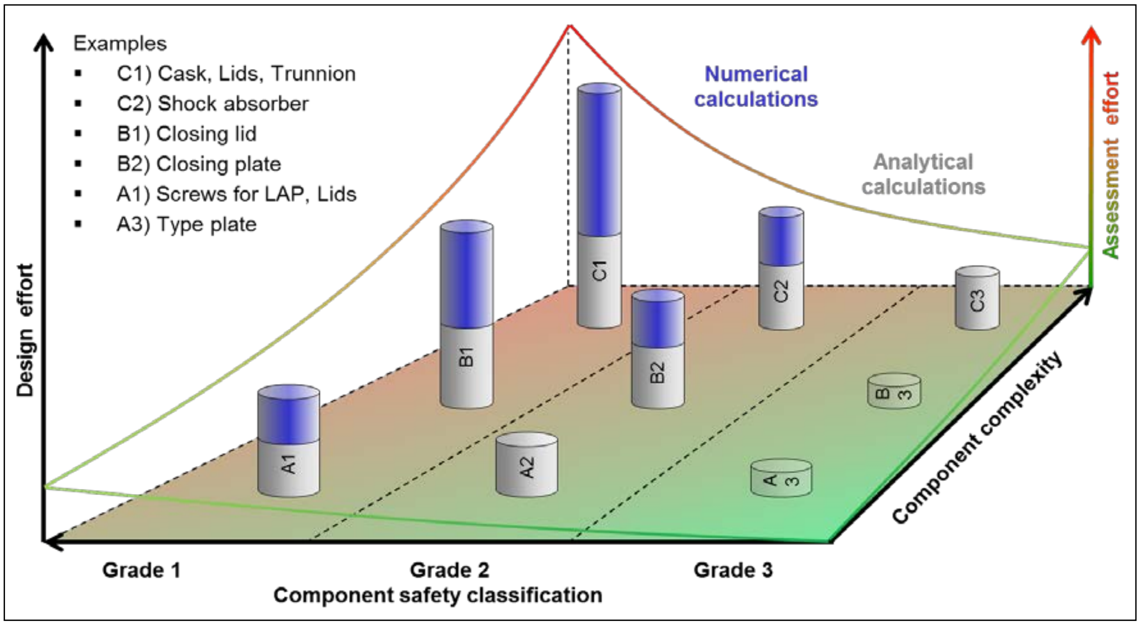


Fig. 1. Main influences on effort for design and assessment

As before the safety relevance classification grade of a component, also the complexity of a component can be differentiated between three grades (Fig.1, A: not complex, C: very complex). Some examples of components with different safety classification and complexity grades are indicated. The corresponding effort for design phase was schematically divided into analytical and numerical parts. As already noted, the effort for component design is increasing if component complexity and safety relevance are increasing. The experience shows that the effort for the assessment phase is increasing in the same way as for the design from A3 to C1 according Fig. 1.

Therefore it is necessary to use effective possibilities to reduce effort on the assessment procedures, especially concerning the numerical part, but without impairing the safety requirements.

As shown, design calculations for complex and safety relevant components and their assessment can be sub-divided into an analytical and a numerical part. Concerning to the analytical part the possibilities for assessment optimization are rather small due to the given standards or guidelines wherein the analysis procedures are described. More potential for optimization is seen in the numerical part, due to a specific assessment path.

Assessment of numerical analyses

The general requirements for numerical analyses are specified in the German guideline BAM-GGR 008 [5]. This guideline provides instructions concerning verification and validation of numerical models. In the following only the general assessment path for the evaluation of numerical analyses is described.

The assessment of numerical calculations can be done in several steps. It is not necessary to perform all test steps listed below. The examination can be completed once the results of the design calculations are confirmed with reasonable reliability and precision. In any case, the input and the output values have to be checked. The input values define the geometry and the mechanical properties of the component in the model. It is to be assessed whether the real behavior of the component is mapped accurately enough despite of idealizations. The geometry, the representation of material behavior, the loads and the boundary conditions including contact formulations should be checked in detail by comparison with drawings or CAD files, parts lists, material specifications, regulatory requirements, etc. The modeling should reflect the state of the art represented in the current literature. Output values of the numerical calculation are the basis of the component's safety evaluation to be performed, wherein different output values are needed depending on the type of the evaluation. Usually stresses for strength verifications, stress ranges for fatigue strength verifications and deformations for the usability and leakage checks are analyzed. But, if strain-based criteria are used, the accumulated plastic strain or, if stability checks are carried out, the collapse load, as a quantity which characterizes the entire system, can be of interest. In any case it has to be checked whether the relevant results were properly taken from the numerical model.

Comparative analytical calculations provide the opportunity to review the results of numerical calculations quantitatively. Often at least the order of magnitude of a result and thus the plausibility of a numerical model can be checked with an analytical calculation. The possibilities and limitations of analytical calculations will be discussed more in detail in the next chapter.

For the check of a numerical calculation it is desirable that the entire content of the corresponding calculation directory is submitted by the applicant. In this way the risk of a different processing status of the input and output data due to confused files decreases. Is there a doubt that the input and output files are associated properly, it makes sense to randomly repeat the calculation of individual load cases without prior changes to the model.

A recalculation after change of model parameters will be performed if e. g. the sensitivity of the model response as a function of variations of input parameters shall be investigated or loads must be adjusted because load assumptions are not sufficiently conservative.

Most extensive is the independent component analysis with own comparative numerical calculations. This can be necessary if the examination steps described above are insufficient to evaluate the numerical analyses provided by the applicant due to high component complexity and/or high safety related requirements.

COMPARATIVE ANALYTICAL CALCULATIONS

General approaches for analytical calculations

The methods for comparative analytical calculations are generally based on the fundamental theories of structural mechanics. There are good technical sources to find equations and examples of application, e.g. [8], [9], [10].

Sometimes the component of a package can be simplified to a basic structure and a corresponding analytical approach may be applied. As an example, the beam theory can be used for bolts of lids and trunnions. The plate theory is applicable on lids and closing plates under the effect of internal pressure or inertia. The shell theory may be employed for a cask body with the effect of a puncture bar drop test.

The state of stress in the contact area of a trunnion in a bearing area can be assessed using the Hertzian contact mechanics formulas. But it is important to be aware of application limits of the mechanical theories.

Examples

The following examples concentrate mainly on bolted joints, which have found wide use in packages to connect lids, trunnions and some other components. The complex mechanical behavior of such a connection type is characterized by stiffness of the bolts and claimed parts, assembly pretension, friction conditions, etc. In relation to safety relevant requirements bolted joints can be found in all three classification groups. For example, trunnion and lid connections are classified in grade 1. According to the guideline for analysis and assessment of bolted lid and trunnion systems BAM-GGR 012 [7], the FE method is to be used preferably in the analysis of such structures to obtain more accurate and detailed information about their stresses. The methodical aspects of FE modeling and corresponding assessment concepts for lid and trunnion systems are discussed in [11] and [12]. In this paper possibilities and limits of analytical approaches as plausibility checks of numerical analyses are considered.

Bolt connection under lid displacement

In the first example the bolt loads due to lateral displacement of the clamped plate are considered (Fig. 2). Such loading can occur in the lid connection under horizontal drop conditions or in bolted trunnions due to crane operations if the lateral force exceeds the friction resistance on the flange surface.

The numerical model has three parts. The bolt size is M30x120 and behaves linear elastic. The plate (48 mm thick) and the basic solid (72 mm thick) are assumed as rigid. To get a good contact behavior the contact area under the bolt head is meshed very fine. The bolt is tied with the basic solid. The friction coefficient under the bolt head was set to 0.2. In the first calculation step the pretension of 200 kN is simulated in the bolt. In the second one the plate is shifted 1 mm to the left. The results show cross section forces and stresses after pretension and at the end of the second calculation step.

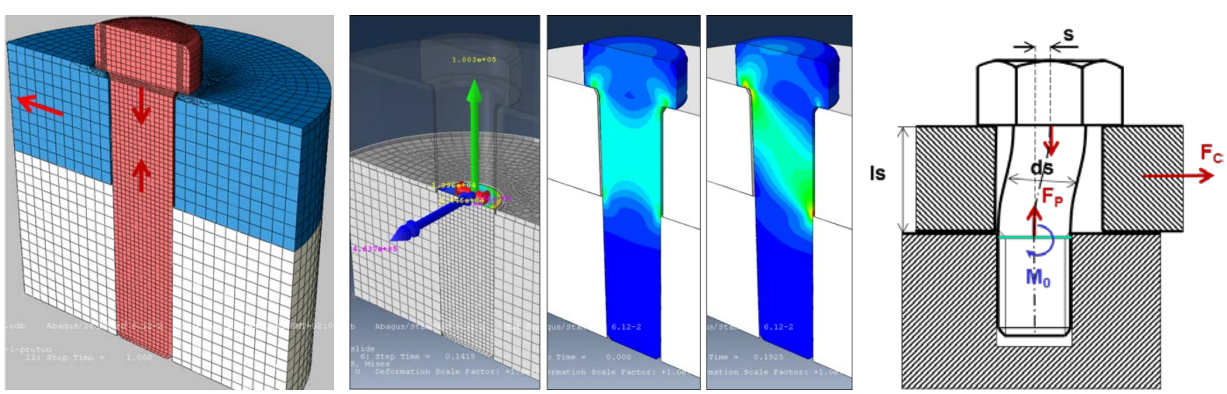


Fig. 2. Models and numerical results for bolt bending due to lid displacement

The classical (Bernoulli) beam theory was chosen for analytical estimation of the bolt bending (Table II). Geometrical and structural properties are equal to the numerical model.

TABLE II. Analytical equations for bolt bending

Lateral force	**Max. displacement of bolt head**	**Bending moment due to $\boldsymbol{F_P}$**	**Bending moment due to $\boldsymbol{F_C}$**	**Pretension stress**	**Bending stress**
$F_C = F_P * \mu$	$s = \frac{F_C * ls^3}{12 * E * I}$	$M_{0s} = \frac{F_P * s}{2}$	$M_{0l} = \frac{F_C * ls}{2}$	$\sigma_P = \frac{F_P}{A_s}$	$\sigma_M = \frac{M_0}{W_s}$

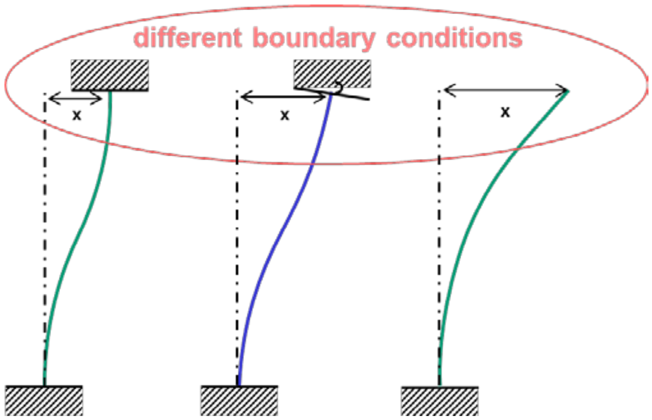
Relevant values for bolt bending due to plate displacement are listed in Table III to compare analytical and numerical results. The results obtained by the two methods are close together except the displacements of bolt head.

TABLE III. Comparison of analytical and numerical results for bolt bending

Value	**numerical results**		**analytical results**	**Description**
Axial force	200 kN	=	200 kN	given load
Lateral force	40 kN	=	40 kN	due to friction with μ=0.2
Moment	928 Nm	≈	956 Nm	same lateral force, but small head rotation
Pretension stress	288 MPa	≈	283 MPa	only pretension without bending or torsion
Maximum stress	633 MPa	≈	644 MPa	lateral force from friction is decisive
Displacement of bolt head	0.110mm	>	0.044 mm	due to small head rotation, short shaft length

This deviation has two reasons. On the one hand the bolt head rotated slightly in the numerical simulation, like in reality. This rotation was not considered in the simple analytical approach (Fig. 3). On the other hand the bolt diameter to length ratio (1:1.6) is beyond of the scope of the Bernoulli theory (<1:5).

The improvement of beam stiffness was carried out by using the Timoshenko beam theory and taking into account the shear stress effect.



Bolt head displacement (x) in mm

Theory / BC	fixed	undefined	free
Bernoulli	0.044		0.177
Timoshenko	0.081		0.212
FEM		0.110	

Fig. 3. Consideration of undefined boundary conditions

The calculations corrected for these effects show that the numerical result of displacement is between the analytical results for fixed and free bearing. Furthermore this example shows clearly the importance of a deliberated choice of analytical approach for a check of numerical results.

Deflection and local opening of lids due to ACT acceleration

The calculation example deals with a simplified system of a primary lid (∅ 1.7 m, max. thickness 300 mm) and a secondary lid (∅ 1.94 m, thickness 95 mm) each with 45 bolted joints M42 respectively M36 and a cask flange area. The lid and the cask consist of the European forged steels 1.4313 and 1.4922, the bolts are made of 1.6582. Each lid has two grooves in the bearing region to maintain an elastomeric O-ring and a metallic gasket. Bolt pretension, reaction forces of the clamped metallic gaskets as well as inertia of cask content (30 metric t) and lid system components due to axial acceleration of 50 g (9 m drop orientation on lid side) are considered as loads.

The widening in the region of metallic seals is of particular interest for the evaluation of the tightness of the lid system. Thus the widening is determined numerical and by an analytical comparison calculation.

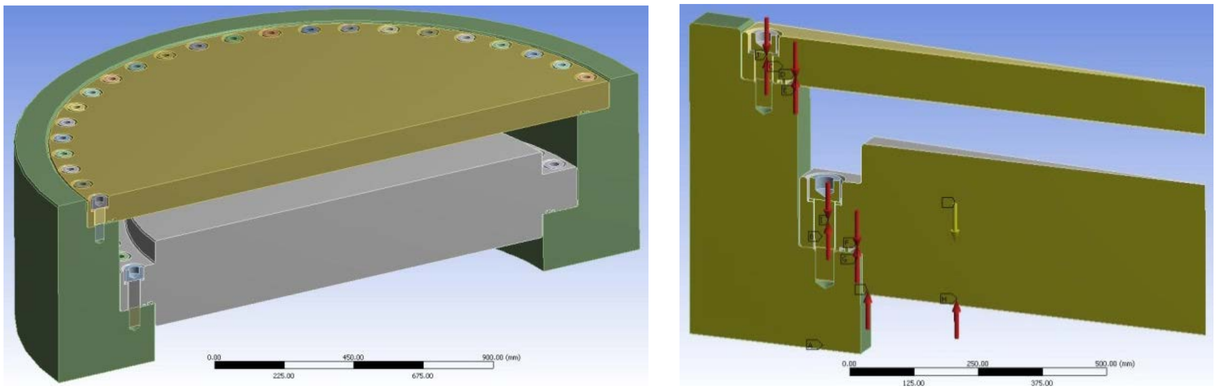


Fig. 4. Lid system, discretized slice model

Since the present example deals only with axial loads, it is sufficient for the numerical calculation to discretize only a sector of the structure as shown in Fig. 4. On the cut surfaces of this sector symmetry boundary conditions are defined. The lower region of the cask wall is supported in axial direction. The bolts are tied to the cask body. Friction conditions are defined for other contact pairs. The simulated loads are applied sequentially. The inertia of the content is taken into account via a pressure load to the inside of the primary lid. Fig. 5 shows the results of the finite element calculation.

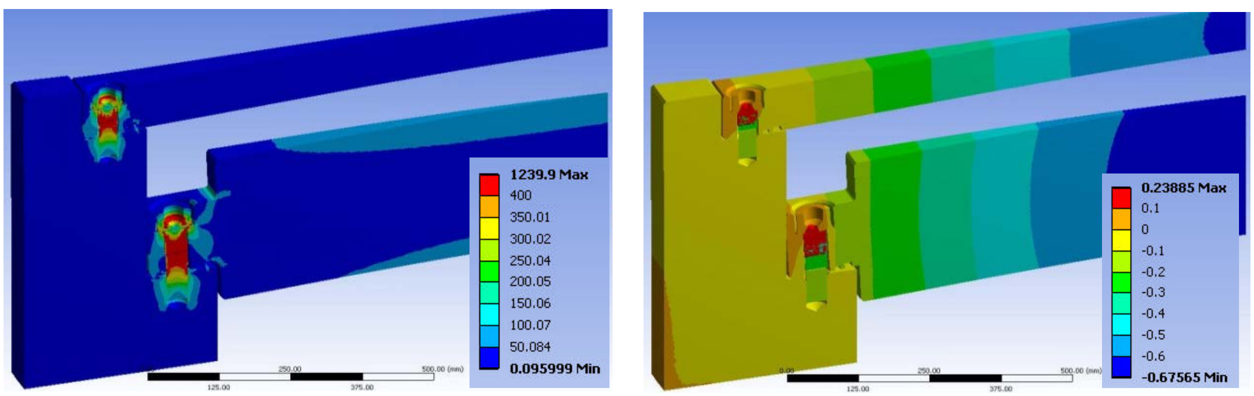


Fig. 5. FEA results: equivalent stress [MPa], deformation [mm] in vertical direction

Basis of the analytic comparison method is the classic Kirchhoff plate theory. The differential equation in polar coordinates for the circular and annular plate under rotationally symmetric surface load is:

$$w^{IV} + \frac{2}{r} w^{III} - \frac{1}{r^2} w^{II} + \frac{1}{r^3} w^{I} = \frac{p(r)}{K} \qquad\qquad K = \frac{E\,t^3}{12(1-\nu^2)}$$

Herein r is the distance from the symmetry axis, w is the deflection, p(r) is the surface load, K is the bending stiffness of the plate and E and ν are Young's modulus and Poisson's ratio.

The general solution of the differential equation for the special case of a constant surface load is used. The solution for the deflection contains four integration constants. Since the primary lid is loaded by a line force at the place of the metallic gasket and the lid also has a change in thickness, the lid can be represented by combination of two annular plates and a central circular plate. The solution for each plate contains four constant of integrations, a sufficient amount to satisfy twelve boundary and transition conditions. Since the rigidity of the edge clamping of the plate by the bolts is difficult to simulate analytically, two limiting cases are examined: on the one hand the lid is clamped in the area of the bolt pitch circle, on the other hand a simple support at the outer edge is assumed. The first model applies approximately for a heavy-duty bolted joint, the second for a light-duty joint.

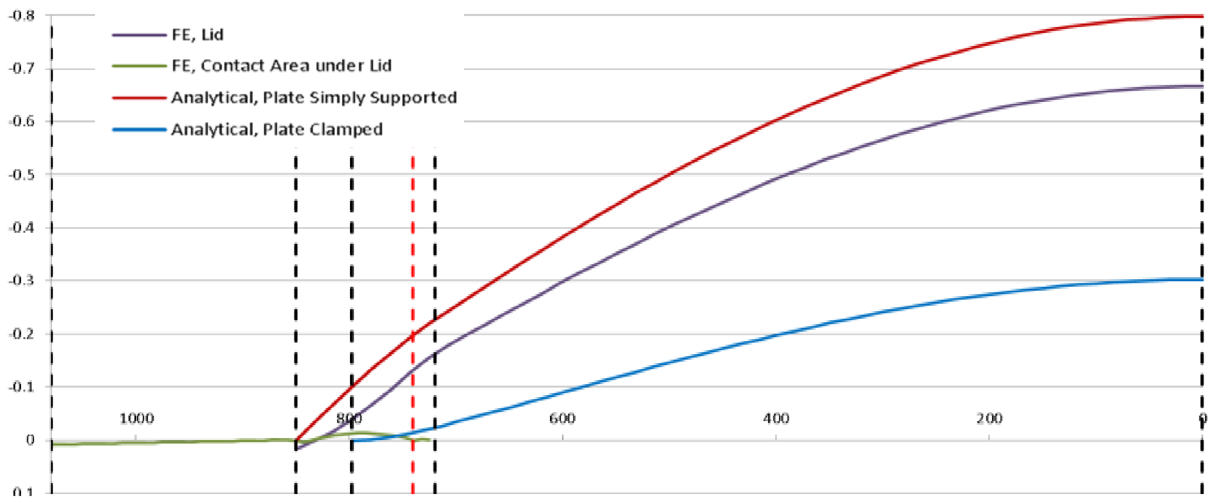


Fig. 6. Comparison of results, primary lid deformation [mm] in vertical direction

In Fig. 6, the numerical and analytical results of the deflection of the primary lid are compared. The numerical results were obtained along horizontal evaluation paths through the cask cutout and the primary lid. The result of the finite element analysis is between the limiting cases analytically investigated.

Trunnion under operational loads

For a correct design of a trunnion an exact strength analysis including fatigue evaluation has to be performed. The compact shape of a typical trunnion (relation of height to diameter) combined with evaluation points near the load exceed the formal applicability of the conventional analytical methods. It is not reasonable to reduce a trunnion to the structure of a beam or a closed circular ring because the application limits of the corresponding basic mechanical theories are significantly violated.

The complex stress field (Fig. 7) under operational load can be adequately investigated only by numerical approach as requested in [7].

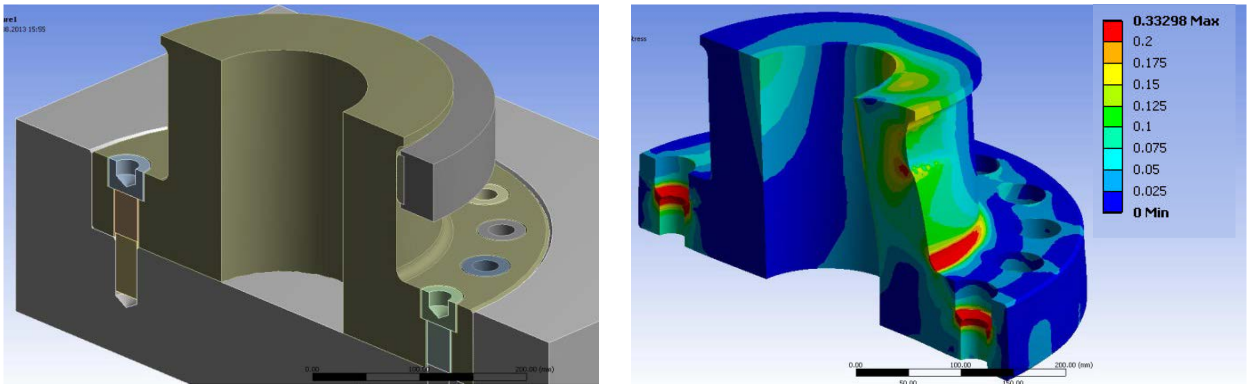


Fig. 7. Numerical model of a trunnion

However some loading characteristic as for example the contact pressure between trunnion and crane link should be estimated analytically or by post-processing of numerical results.

CONCLUSION

The effort for component and package safety analyses increases with increasing component complexity and increasing safety relevance. Experiences of BAM and TÜV show that the assessment effort increases in the same way as for the design phase. Therefore it is necessary to search for an enhanced assessment strategy, especially in the numerical range, but without impairing the safety requirements.

As shown, design calculations can be sub-divided into an analytical and a numerical part. In the analytical part the possibilities for assessment optimization are rather small due to the given standards or guidelines. More potential for optimization is seen in the numerical part. There are more possibilities like standardization of the models or the application of new methods for model generation. The present paper describes the use of analytical approaches within the assessment strategy of numerical analyses to reduce the effort of assessment. With three examples it has been shown which possibilities and limits exist to support the assessment of numerical analyses using analytical calculations for comparison.

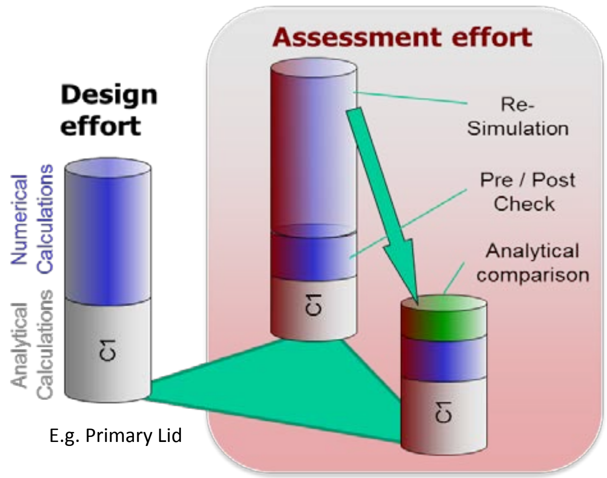


Fig. 8. Span of assessment effort

The application of verified basic structural mechanical theories in relation to the deformation behavior of the component can lead fast to comparable results or a good localization of the solution area. But scope and limits of the theories have to be considered. The bolt-lid example shows the influence of component and boundary stiffness on the results. Thickness to length ratio is higher than specified in the structural mechanical theories and only fixed or free boundary conditions could be analyzed analytical. Nevertheless the analytical approaches could help to evaluate the numerical results for the assessment. The example of a trunnion demonstrates the limits of analytical approaches. The trunnion shows a complex deformation behavior and local stresses. A single basic theory isn't matching and a construct of several approaches is not useable for calculations of local stresses. Therefore numerical calculations during assessment are necessary for this safety case.

Analytical approaches are not always useable but often effective to reduce the effort of assessment.

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